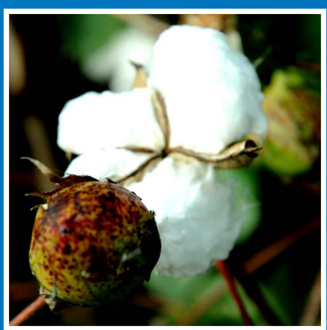
WATERpak

a guide for irrigation management in cotton and grain farming systems



Australian Government
Cotton Research and Development Corporation

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Best Practice

WATERpak – a guide for irrigation management in cotton and grain farming systems

Australian Government
Cotton Research and Development Corporation

Edited by Helen Dugdale, Graham Harris, James Neilsen, Dirk Richards, David Wigginton and David Williams for the Cotton Research and Development Corporation.

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Disclaimer and warnings

The information in this publication is designed as an information source to improve the sustainable use of water on irrigation farms in eastern Australia growing cotton and grains.

The information has been prepared from research studies and grower trials with specialist input from researchers, extension staff and irrigators. While these authors provide comprehensive coverage of on-farm water-related issues, they do not purport to address every eventuality that may arise on irrigation farms.

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Foreword

The 2013 edition of WaterPAK is a compilation of the latest best practice management information for water management on Australian cotton farms.

Water is the major limiting factor for cotton production in Australia and efficient water management is paramount for cotton growers to achieve high yields and profits in a sustainable way. Making good water management decisions is no simple task for growers who operate in a complex environment of unpredictable climate, variable soil type and evolving water policy.

In the face of these challenges the cotton industry has improved its efficiency of turning water into bales of cotton by 40 per cent over the last 10 years and growers are equally ambitious for future improvements. This edition of WATERpak provides growers and consultants with the best available information from research to assist them make further improvements in water use efficiency and water management more broadly. WATERpak is a supporting information resource for the cotton industry's Best Management Practice program myBMP.

CRDC and the industry have long recognised the connection between more efficient water use and improvements in environmental outcomes on farms. New goals for both are guiding cotton industry investment in research and development concerning water and water use. These goals will be facilitated through the turning of knowledge into practise on every farm where growers reap the value every season from improvements to system design and management, the selection and adoption of new technologies, a management focus on the water needs of cotton plants and a better understanding of how to respond to a variable climate.

Keeping step with research, included in this edition are new chapters looking at tools and information for decision making, irrigation system selection, storages and channels, pumps, fertigation, and management decisions in limited water use situations as well as a new section dedicated to irrigation management of grain crops.

WATERpak has now been designed to be read electronically on tablets and notebooks, with links to other on-line information sources so further information can be readily accessed. As new research comes to hand, this is further developed by the Cotton Industry Development and Delivery Program and its team of specialists. WATERpak will be regularly updated and distributed electronically to growers and their advisors.

Like its predecessor, this publication of WATERpak demonstrates that the Australian cotton industry is taking its responsibility for wisely managing the use of water resources seriously. Equally it demonstrates the capacity of our world leading industry researchers, development and delivery personnel. Well done.

Bruce Finney

Executive Director, CRDC

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About this publication

Water is the major limiting factor of cotton and grain production in Australia and efficient water management is paramount for cotton and grain growers to achieve high yields and profits. An unpredictable climate coupled with a range of soil types forces farmers to make management decisions in a complex and variable environment.

The challenge for irrigators is to find the balance between the higher costs of improved water use efficiency and environmental stewardship and the maintenance of farm profits.

WATERpak provides technical information and practical advice to help irrigators improve irrigation practices, minimise environmental impacts and increase farm profits from irrigated cotton crops.

For the first time, WATERpak brings together in one place the many years of irrigation research conducted by a variety of organisations in the Australian cotton and grains industries.

The easiest gains to improve farm water use efficiency are within the field: minimisation of tailwater losses, drainage and the potential improvement in yield through the reduction of waterlogging effects. Put simplistically, by 'applying the right amount of water at the right time in the right place'.

Harder to achieve but very significant in terms of water use efficiency, gains exist in the control of evaporative and seepage losses from storages and channels. This is where most water is lost on broadacre irrigation farms and it is essential that researchers and growers combine forces to address evaporation, seepage and drainage losses.

This third edition of WATERpak brings together best practice for irrigation managment in the cotton and grains industries, whether as part of an integrated farming system or as separate enterprises.

WATERpak and myBMP

The Cotton Industry's myBMP Program prioritises issues for attention, provides a process of identifying the potential management risks and provides action plans to help manage those risks and improve farm performance.

WATERpak provides detailed technical and practical advice that supports the practices covered in the water module of myBMP. Individual myBMP practices provide links directly to the relevant WATERpak resources and a more detailed explanation of these links is included in WATERpak Chapter 1.1.

Another companion resource is *SOILpak for cotton growers*, generally referred to simply as SOILpak in this publication.

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Section 1

Concepts for Efficient Irrigation

1.1 Farm planning, WATERpak and myBMP

Why Planning?

Planning simply means thinking ahead - vital to the success of any farming operation. Planning helps to:

- Understand farm resources, especially water, soils and infrastructure that are the foundations of any agricultural operation.
- Identify issues and potential challenges facing your business, allowing timely intervention or preparation.
- Formulate goals and strategies that can guide day to day management decisions.
- Maximise business performance by minimising risks, minimising costs and maximising returns.

The initial planning step involves assessing and recording a farms resources and then identifying what risks or management issues need to be considered. You can then develop goals, strategies and action plans for how you manage your valuable farm assets as efficiently and responsibly as possible. Good planning is essential to ensure that the wide range of potential issues and factors affecting an irrigated cotton or grain farm are taken into account.

Unfortunately there are many complicated and interrelated factors and processes involved in water management in irrigated farming systems and extensive knowledge is required to address on-farm water losses in the areas of seepage, evaporation, deep drainage and run-off. Fortunately, many improvements in water use efficiency can be easily gained through changes to management practices which don't necessarily require extensive farm redevelopment or irrigation system upgrades. Indeed, the experience captured within this publication demonstrates a wide array of practices and technologies that can dramatically improve water use efficiency.

The cotton industries Best Practice initiative, myBMP, can also support you in the process of farm planning by helping to identify potential risks that may be associated with a particular activity and then providing advice for managing those risks. Practices in myBMP represent a step-by-step checklist which can be used as a guide to risk management and better farm planning.

A good plan should not only allow you to maximise water use efficiency and return per megalitre: it should mean that you achieve the standard of environmental management expected by both the industry and the community. In fact, myBMP branded cotton is becoming increasingly desirable to consumers as it demonstrates a commitment to environmentally responsible production.

WATERpak and myBMP are both excellent tools that can be used to develop a full farm plan, identify improvement options and benchmark your farms water use against industry standards.

Using WATERpak to support myBMP

The myBMP program is fully supported by the latest information, tools and resources available from the cotton industry research and extension community meaning that growers have direct access to this knowledge from a centralised location. This makes myBMP a key delivery tool for industry research and extension.

WATERpak is a key information source supporting the water module of myBMP. This module covers topics ranging from the water source (storages, bores, overland flow and stored soil moisture) through the application of irrigation to fields to the management of potential irrigation impacts such as deep drainage, water quality and salinity. All irrigation systems are covered including surface irrigation, centre pivot, lateral moves and drip irrigation.

Once you have completed the myBMP Water module to at least Level 2 you will have achieved the following:

- used available tools to schedule your irrigations and monitor soil water levels;
- estimated your soils capacity to hold and store water for your fields and soil types;
- estimated your losses from storages and channels;
- maintained your storages to minimise leaks and seepage, particularly in dry times;
- maximised crop yields by understanding and managing bore water quality;
- calculated and recorded your irrigation water use index;
- identified problem areas in irrigation fields and addressed them;
- matched your flow rates to soil, slope and run length so furrows come out evenly;
- planned for and installed your centre pivot or lateral move with a professional so it works effectively; and,
- ensured your drip irrigation system is operating effectively.

Individual practices within myBMP provide links directly to the resources that support these practices, including the specific chapters within WATERpak. The list below provides a brief summary of each of the key areas within the water module of myBMP and the way in which WATERpak provides support.

myBMP Key Area	Description	WATERpak support
Whole farm water recording and performance	The measurement of irrigation water and crop water use is critical to understanding farm water management but can be difficult to do. Once the basic information is known, a range of performance indicators can be calculated so that performance can be improved. Developing a whole farm water balance with strategies to encourage improvements in water use efficiency are the ultimate in performance benchmarking.	WATERpak provides information on water metering, measurement of crop water use and soil water as well as water budgeting. A range of performance indicators are described along with methods for their calculation. Whole farm water balance techniques are provided for advanced managers.
Field water management and performance	Measurements of water use can also be made at the field level with the data used to benchmark and improve performance. In addition, EM surveys provide additional field information and the role of deep drainage should be understood.	WATERpak provides detailed information on metering techniques and performance measurements for different irrigation application systems. Practical information on EM surveys is also included and the theory and research into deep drainage is thoroughly described.
Crop and soil water management	Understanding crop and soil water requirements allows scheduling and crop management to be optimised. This can lead to yield improvements as well as water savings.	These sections of WATERpak have been thoroughly updated to include the latest research on Bollgard cotton. In addition, dedicated chapters for the major irrigated grain crops are included for the first time. Information on soils, scheduling and crop agronomy has also been improved and reorganised so that it better supports myBMP.
Water storage and distribution management	On-farm storages are the main source of water loss on most irrigated cotton farms, so optimising their management is critical to maximise water use efficiency.	A brand new chapter on measuring and managing water storages and distribution channels has been included in this edition of WATERpak, reflecting the latest research undertaken in recent years.
Surface irrigation systems	With the majority of irrigation in the industry undertaken using surface irrigation systems, managing their performance is extremely important. A range of practices are included to optimise management and improve performance.	The development of surface irrigation systems is covered, as well as a new section on surface irrigation performance and management. New information on recent research into bankless channel and pipe through the bank systems has also been included.
Drip irrigation systems	The design, installation and management of drip irrigation are absolutely critical to achieving high water use efficiency with this irrigation system.	WATERpak provides an overview of drip irrigation systems for cotton irrigation as well as advice on installation, management and maintenance.
Centre pivot and lateral move systems	The popularity of CPLM systems has increased in recent years, a trend which is predicted to continue. As is the case with drip systems, CPLM design and management is critical to achieving high performance and long life.	WATERpak includes information on critical design parameters, operating information and energy use as well as information on cropping systems under CPLM systems. Measurement of system performance is also included.
Bore Management	Groundwater is a major water source for many cotton and grain irrigators. Bores need to be properly maintained to ensure a long life. Groundwater quality can vary over time and should be monitored regularly to ensure it does not detrimentally affect crop growth. Similarly watertable levels should be monitored over time to identify any changes that could impact on water security in the future.	A new section on bores is to be developed and included in a future edition of WATERpak. Information on water quality and the impacts on crop growth is included in this edition.
Dryland water management	Many irrigators also grow dryland crops and myBMP includes a number of practices to enable growers to maximise rainfall capture and most efficiently convert this water into yield.	WATERpak does not have dedicated information on dryland cropping, although much of the information contained in WATERpak regarding crop agronomy and soil management is useful in dryland situations. myBMP provides a range of references to other specific dryland cropping resources.
Tailwater and stormwater management	myBMP contains practices that limit the risk of offsite impacts from irrigation properties due to tailwater and stormwater runoff.	Tailwater management is discussed in the WATERpak chapter on surface irrigation systems. WATERpak also includes further information on water quality and buffer zones as well as references to other publications that provide more detail in this area.

1.2 Water use efficiency, benchmarking and water budgeting

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Key points

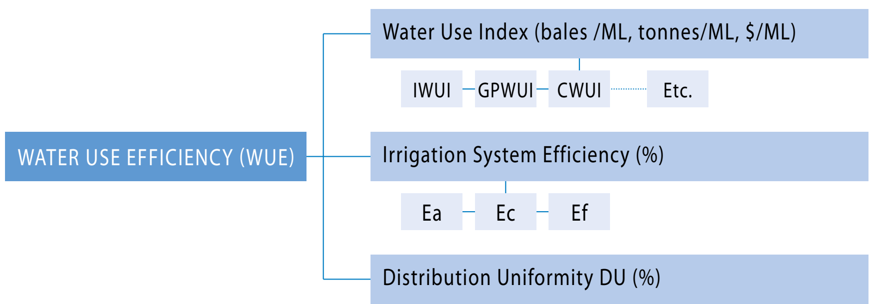
- Water Use Efficiency is a generic label that encompasses an array of performance indicators used to describe water use within a cropping system.
- A Water Use Index (WUI) relates production outputs ($, bales, tonnes, etc.) to water input (ML).
- An Irrigation System Efficiency (%) relates water output (ML) to water input (ML).
- It is important to always understand the inputs and dimensions of water use efficiency terms as well as the scale at which they are applied.
- Benchmarking involves comparing performance indicators or management processes.
- A water budget is used to determine how best to use the available water resource by balancing seasonal risks

Water Use Efficiency (WUE) is a concept that has historically caused much confusion for scientists, water suppliers and end users alike. Much of this confusion has stemmed from the range of terms available to describe water use efficiency and a lack of understanding of what WUE represents. The Australian irrigation industry developed a framework (Barrett, Purcell and Associates, 1999) to standardise the array of terms and definitions used to minimise this confusion. The concepts and definitions employed in WATERpak reflect this framework.

Water Use Efficiency is itself a generic label that encompasses an array of performance indicators used to describe water use within a cropping system (Figure 1.2.1). The performance indicators can be categorised as one of the following:

- Water Use Index (WUI) (relating production to water use)
- Irrigation System Efficiency (relating water inputs to water outputs at different locations)
- Distribution Uniformity (DU) (a measure of how even an irrigation application is)

Figure 1.2.1. Irrigation performance indicators.

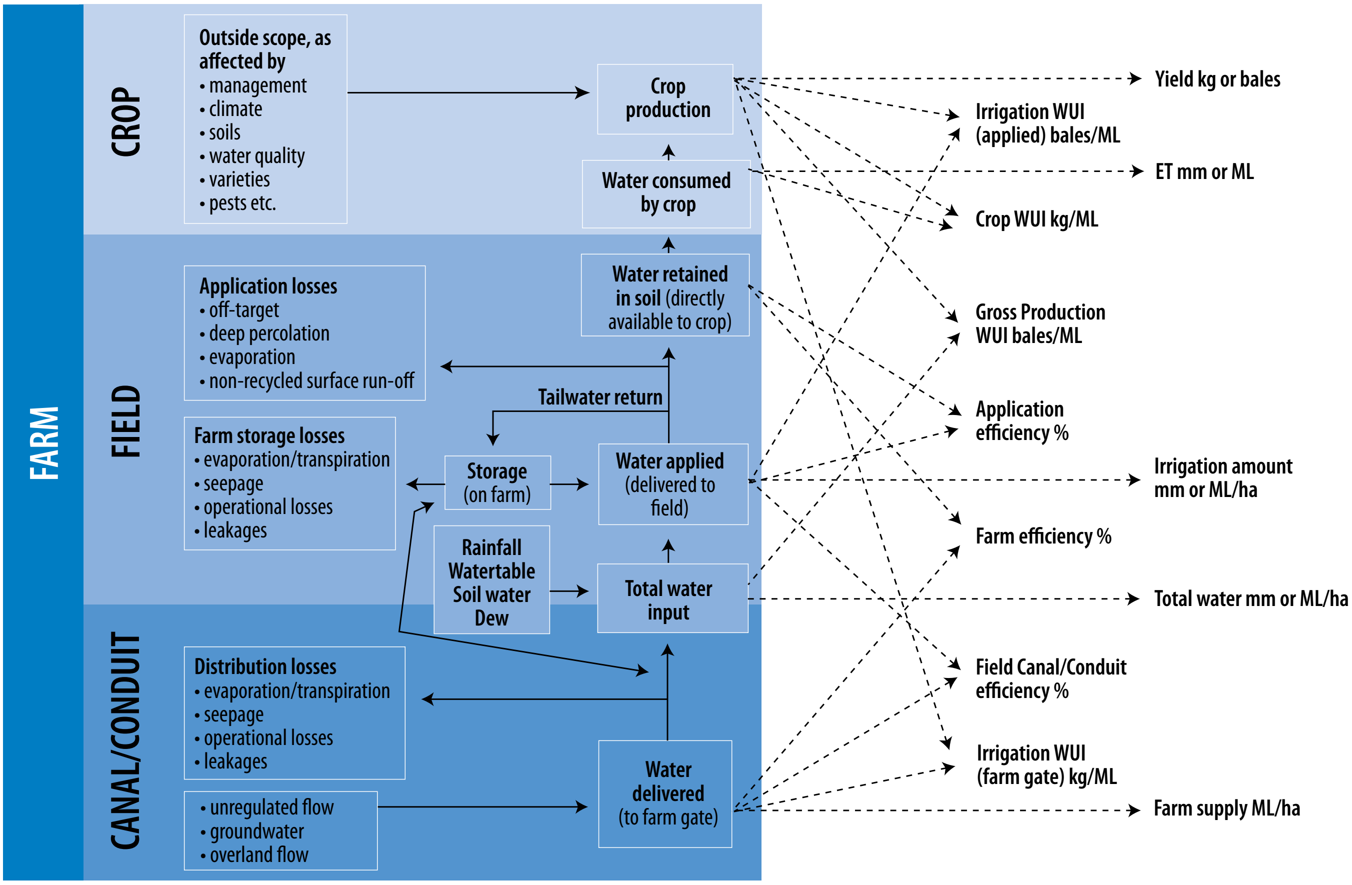


Different indicators can be used in different situations according to the intended purpose, inputs, outputs and boundary conditions. Boundaries, both spatially (area) and temporally (time) need to be specified. Area boundaries might include a field, farm or region whilst time boundaries could be a single irrigation event, a month, the growing season or a year.

Due to the complexity of the system it is not practical to calculate all the possible water use efficiency indicators, nor is it necessary, as a meaningful picture of water use efficiency is obtained through calculation of those indicators with the most pertinence.

The relationship between these performance indicators at different scales within an entire irrigation system is illustrated fully in the framework provided in Figure 1.2.2

Figure 1.2.2. Framework for on-farm water use efficiency

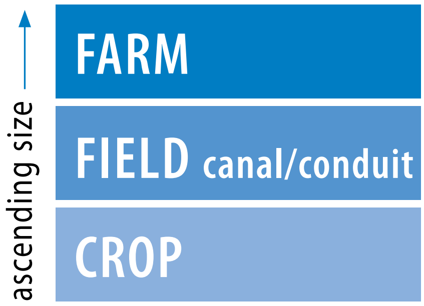


Source: modified from: Barrett, Purcell and Associates, 1999

As previously discussed and indicated in Figure 1.2.2, indices and efficiencies can be calculated over a range of spatial boundary conditions (scales). This concept is important for calculation of WUE indicators because:

- Indices are differentiated on the basis of the scale at which they are applied. For example, Irrigation Water Use Index (Applied) and Irrigation Water Use Index (Farm) both compare yield and irrigation water input but are applied at different scales, the field and farm respectively. Therefore it is important to understand at which scale the inputs have been measured.
- As will be discussed later, efficiency terms at different spatial scales are all related, so that they may be multiplied together to gain an efficiency at the next greatest scale. This concept is termed a 'nested' approach.

The order of spatial scales is as follows:



Effective Rainfall

Before discussing water use efficiency terms in more detail, it is worth briefly discussing effective rainfall, as this is an important concept for some specific terms. Rainfall is considered effective if it contributes to the water requirement of the crop.

Effective rainfall includes:

- water intercepted by vegetation,
- soil evaporation losses,
- evapotranspiration losses; and
- the contribution to leaching requirement.

Ineffective rainfall includes:

- uncaptured surface runoff,
- deep drainage; and
- any remaining soil moisture that is not used for subsequent crops.

In the simplest of terms, accounting for the major losses, effective rainfall is approximated by:

Effective rainfall =

total rainfall – run-off – deep drainage

This definition assumes that variables such as rainfall intensity and initial soil moisture (rain falling on a full soil profile has little effectiveness) are taken into account by the runoff and deep drainage terms; however these terms themselves can be quite difficult to measure.

Effective rainfall can also be estimated using:

- Computer programs such as Watertrack™ and HydroLOGIC
    - HydroLOGIC is cotton specific and accounts only for losses due to run-off.
    - Watertrack™ accounts for both run-off and deep drainage losses.
- The change in soil moisture due to rainfall. This method relies on the accuracy of the measurement equipment (most soil moisture probes give only approximate values - see WATERpak Chapter 2.7), does not indicate the volume of water lost through the profile and does not account well for spatial variability.
- A guess of the effective proportion: it is sometimes taken that 75% of the rainfall for the season is effective.

It is important to note that all of these methods include some substantial assumptions, particularly the soil moisture measurement and 75% methods.

Water Use Indices

Water use indices typically compare a production output (yield, return, gross margin) to a water input (such as irrigation water, total water or evapotranspiration) at some level in the farm or production system. In other words, they compare two different units (bales/ML, $/ML, kg/mm, etc.).

- They are very flexible and can be tailored to a particular situation, but can be quite easily used out of context if the units are not well defined.
- Production can be defined in terms of yield (bales or tonnes), lint yield (kg), gross return ($), gross margin ($) or any other appropriate measure.
- Water inputs are usually defined in terms of crop water use (mm), irrigation water input (ML) or total water input (ML). Such water inputs across a whole farm may include water pumped from rivers and bores, the amount used from storage reservoirs, water harvested during the season, effective rainfall or total rainfall and soil moisture reserves depleted during the season.

As discussed previously, Water Use Indices can be applied at different spatial scales within the farming system. This concept is very useful as it allows for comparison of production and water use at very specific locations (crop scale), within individual management units (field scale) or to assess the performance of the whole farm. By calculating WUI's at these different scales, appropriate management options can be formulated to try and improve the effectiveness of water use.

Water Use Index (IWUI)

Irrigation water use index is a measure that relates the total amount of production to the amount of irrigation water that was applied to produce this yield. It is a useful measure and is commonly used, particularly for internal analysis, as it only accounts for irrigation water and therefore it can reflect differences in irrigation management. However it is less useful as a comparison, particularly between different farms or regions, as it takes no account of differences in rainfall (which can significantly influence the amount of irrigation required).

IWUI can be applied to either the field or the farm scale.

Field scale:

Irrigation water use index (applied) (%) =

$$\frac{\textbf{total yield} \text{ (bales)}}{\textbf{irrigation water applied} \text{ (ML)}}$$

Farm scale:

Irrigation water use index (farm) (%) =

$$\frac{\textbf{total yield} \text{ (bales)}}{\textbf{irrigation water supplied to farm gate} \text{ (ML)}}$$

For example, a cotton field has a yield of 80 bales and 50 ML of irrigation water was applied to the field during a season.

IWUI (applied) = (80 ÷ 50) = 1.6 bales per megalitre

Across the whole farm, 450 bales of cotton were produced using 350 ML of irrigation water.

IWUI (farm) = 450 ÷ 350 = 1.3 bales per megalitre

Note that the scale at which the term has been applied has been specified explicitly in each case (applied or farm).

The same calculation can be performed for different crops. For example, on another field, 50 ML of water was applied to produce 160 tonnes of sorghum.

IWUI (applied) = (160÷ 50) = 3.2 tonnes per megalitre

Across the whole farm, 880 tonnes of sorghum were produced using 350 ML of irrigation water.

IWUI (farm) = (880 ÷ 350) = 2.5 tonnes per megalitre

Gross Production Water Use Index (GPWUI)

Gross production water use index is the amount of yield produced compared to the total water input. The total water input includes irrigation, rainfall and total used soil moisture. The rainfall component can comprise either total rainfall or effective rainfall and therefore must be specified. GPWUI can be applied to multiple spatial scales, typically to the field or farm.

Gross production water use index is a measure that is helpful for comparing the irrigation performance of different fields or farms across different regions and seasons because using the total water input helps to account for spatial and temporal differences (in rainfall, for example) that lead to different irrigation requirements.

Although calculation of this index is typically simpler if total rainfall is used, a better result is obtained by using effective rainfall. For example you may wish to compare two fields that both received 350 mm of rain throughout the season. If one field received all of that rain in one event, much more irrigation water would be required for the rest of the season than on another field that may have received the rain in regular, effective events. This may bias the index to indicate that one field produced more yield per ML of water applied even though the actual performance of the irrigation systems may be similar.

Field scale:

Gross production water use index (applied) (b/ML) =

$$\frac{\textbf{total yield}\ \text{(bales)}}{\textbf{total water applied}\ \text{(ML)}}$$

Farm scale:

Gross production water use index (farm) (b/ML) =

$$\frac{\textbf{total yield}\ \text{(bales)}}{\textbf{total water used on farm}\ \text{(ML)}}$$

From the previous example, a cotton field has a yield of 80 bales which used 85 ML of total water (irrigation, effective rainfall and used soil moisture).

GPWUI (effective) (applied) = (80 ÷85) = 0.94 bales per megalitre

Across the whole farm, 450 bales were produced using 530 ML of total water (irrigation, effective rainfall and used soil moisture).

GPWUI (effective) (farm) = (450 ÷530) = 0.85 bales per megalitre

Note that the use of effective rainfall and the scale of the calculation has been made explicit in the title of the term. In this case, the whole farm GPWUI is lower than for the individual field. This is typically the case as the whole farm figure includes additional sources of water loss such as on-farm storages.

A sorghum field has a yield of 160 tonnes and used 100 ML of total water (irrigation, effective rainfall and used soil moisture).

GPWUI (effective) (applied) = (160 ÷100) = 1.6 tonnes per megalitre

Across the whole farm, 880 tonnes were produced, using 490 ML of total water (irrigation, effective rainfall and used soil moisture).

GPWUI (effective) (farm) = (880 ÷490) = 1.8 tonnes per megalitre

In this case, the yield from the field happened to be lower than for the rest of the farm and this meant that the field GPWUI was smaller than the farm GPWUI.

Crop Water Use Index (CWUI)

Crop water use index (CWUI) is an indicator that describes plant-water interactions at the crop scale and is represented as the yield (lint yield for cotton) produced per millimeter of water evapotranspired from a field during the growing season. It is usually reported in kilograms per hectare per millimeter but may also be reported in bales per megalitre.

Daily evapotranspiration data is available from the Bureau of Meteorology and SILO. Such data needs to be converted to daily crop water use using an appropriate crop coefficient as explained in WATERpak Chapter 2.8.

In essence, CWUI represents the ability of the plant to produce yield (rather than vegetative growth) for the given water use. This indicator is influenced by many factors such as variety, nutrition, pests, disease and climate.

Some irrigation management factors (such as irrigation timing and prevention of waterlogging) can affect the amount of energy that is being expended on crop reproduction, thus influencing CWUI. However, because of the wide range of factors that influence the inputs to this index, it provides a broad measure of crop performance rather than a specific measure of irrigation performance.

$$\textbf{CWUI}\ \text{(kg/ha/mm)} = \frac{\textbf{lint yield}\ \text{(kg/ha)}}{\textbf{seasonal evapotranspiration}\ \text{(mm)}}$$

For example: A cotton field with 2000 kg/ha of lint yield and 750 mm of seasonal evapotranspiration:

$$\text{CWUI} = (2000 \div 750) = 2.67\ \text{kg/ha/mm}$$

Note that this term only applies at the crop scale and therefore does not need to have the scale explicitly defined as is the case with the previous indicators.

This figure can be converted into bales per megalitre by dividing by 227 (kg →bale) and multiplying by 100 (mm →ML):

$$\text{CWUI} = (2.67 \div 227) \times 100 = 1.17\ \text{bales/ML}$$

A sorghum field yields 8 t/ha (i.e. 8000 kg/ha) and uses 480 mm of seasonal evapotranspiration:

$$\text{CWUI} = (8000/480) = 16.7\ \text{kg/ha/mm}$$

Economic Indices

Economic indices can be calculated by applying an economic production measure to any of the indices described above. This measure could be gross return, gross margin, marginal return, or any other appropriate economic measure. The economic calculation is typically achieved by multiplying the economic measure and the appropriate WUI, to achieve a $/ML result.

Economic indices can be used to compare the economic return on water inputs. Three economic terms that are often used to generate economic indices are:

- Gross income (GI)
- Gross margin (GM)
- Operating profit (OP)

Whatever economic indices are used it is important to state the inputs and give it an appropriate name. Often the economic inputs used in these calculations can be confusing. The relationships between the economic terms used in these calculations are as follows:

$$\textbf{Gross income}\ (\$) = \textbf{production}\ \text{(bales or tonnes)} \times \textbf{on-farm price}\ \text{(\$/bale or \$/tonne)}$$

$$\textbf{Gross margin}\ (\$) = \textbf{gross income}\ (\$) - \textbf{variable Costs}\ (\$)$$

$$\textbf{Operating profit}\ (\$) = \textbf{gross margin}\ (\$) - \textbf{overheads}\ (\$)$$

- Variable costs are costs that change according to the area of crop grown
- Overheads are costs that do not vary greatly with area of crop grown (fixed costs)

Three economic indices that can be calculated at the farm scale to relate these economic terms to the total water used on farm (including rainfall) are:

$$\textbf{Gross return WUI}\ \text{(farm)} = \frac{\textbf{gross income}\ (\$)}{\textbf{\textit{total} water used}\ \text{on farm (ML)}}$$

$$\textbf{Gross margin WUI}\ \text{(farm)} = \frac{\textbf{gross income}\ (\$) - \textbf{variable costs}\ (\$)}{\textbf{\textit{total} water used}\ \text{on farm (ML)}}$$

$$\textbf{Operating profit WUI}\ \text{(farm)} = \frac{\textbf{total gross margin}\ (\$) - \textbf{overhead costs}\ (\$)}{\textbf{\textit{total} water used}\ \text{on farm (ML)}}$$

The advantages and drawbacks of these economic inidices are provided in Table 1.2.1.

Table 1.2.1 - The advantages and drawbacks of different economic indicators

The advantages and drawbacks of these different economic indices are:

Advantages	Drawbacks
Economic Index – Gross Return WUI	
Easy to calculate as on-farm price is easily obtained	Limited value as gross return is not necessarily a good indicator of profit. Not possible to compare between farms in the same year due to commodity price differences. Difficult to compare between years on the same farm due to commodity price changes from year to year
Economic Index – Gross Margin WUI	
Inclusion of variable costs enables comparison between alternative crops on the same farm.	Differences in variable costs between farms make it difficult to compare this index between farms, particularly those in different districts. Gross margins exclude overhead costs so are not an adequate measure of profit.
Economic Index – Operating Profit WUI	
The inclusion of farm overhead costs to calculate operating profit provides the most meaningful economic index for a farm. The benefit of minimising overhead costs to maximise profits is clearly demonstrated.	Overhead costs can vary significantly between farms so difficult to use to compare between farms. Slightly more difficult to calculate than the other indices because of the need to sum overhead costs for the farm.

Variations on these indices are also possible. For example you could also calculate them using only the applied irrigation water rather than the total water. Note the term is now called an Irrigation Water Use Index (IWUI):

- Gross Return IWUI (farm)
- Gross Margin IWUI (farm)
- Operating Profit IWUI (farm)

Or you could calculate them for individual fields using total water applied or only irrigation water applied. It is important to remember to clearly define the scale at which they are being applied (field or farm) and the inputs being considered (gross return, gross margin, operating profit, irrigation water, total water).

For example, we previously calculated the GPWUI (effective)(applied) for a cotton field to be 0.94 bales/ML. If the cotton price is $400 per bale, we can calculate a gross return per megalitre of total water:

Gross return WUI (effective)(applied) **= (0.94 x 400) = $376** per megalitre

Alternatively, we can calculate the gross return on the irrigation water only. We previously calculated the IWUI (applied) for this field to be 1.6 bales/ML. For the same cotton price ($400 per bale) the gross return per megalitre of irrigation water is:

Gross return IWUI (applied) **= (1.6 x 400) = $640** per megalitre

Irrigation System Efficiencies

Irrigation system efficiencies are different to indices. This is because they compare the water output (or available) to the water input (supplied) at different points of the farm or irrigation system. Efficiencies do not have units, they are expressed as a percentage (%).

Although it is possible to determine the efficiency of any component of the irrigation system, three main efficiency terms are used widely in the irrigation industry and are applicable within the farming system:

- Application Efficiency (E_a)
- Field Canal/Conduit Efficiency (E_b)
- Farm Efficiency (E_f)

The dual use of the terms 'canal' and 'conduit' indicates that this efficiency term is used for any type of distribution system (i.e. it is equally applicable to channels and pipes).

Application Efficiency (E_a)

Application efficiency relates the amount of water supplied to the field to the amount of water available to the crop. Calculation of application efficiency is very useful as it can indicate the potential for water savings within the field and the associated production benefits.

However it can be difficult to determine the amount of water available to the crop, as run-off and drainage losses need to be taken into account. For a system that completely refills the soil profile, the amount of water delivered to the crop may be taken to be the soil moisture deficit prior to irrigation. For systems that only partially refill the soil profile, run-off and drainage will need to be measured.

$$E_a = \frac{\text{irrigation water directly available to the crop for use}}{\text{water received at field inlet}}$$

For surface irrigation systems, the amount of water received at the field inlet may be measured with flow meters installed on pump sites or in pipes that deliver water to the head ditch. For drip and overhead irrigation systems, water applied to the field can usually be obtained from a calibrated control panel or measured directly with flow meters attached to the system.

Under most circumstances, the amount of water available to the crop for use is the amount of irrigation water that is delivered to the root zone, that is, the change in soil moisture (ΔSM). For a system aimed at completely filling the soil profile, this is equal to the target deficit. Note that if actual soil moisture readings are used for this calculation the probes must be calibrated (see WATERpak Chapter 2.7) and that point source readings do not account for spatial variability within the field.

Example:

Furrow irrigation

Soil moisture deficit before irrigation = 70 mm

Soil moisture deficit after irrigation = 0 mm

Water delivered to rootzone = 70 – 0 = 70 mm

Total water applied = 1.2 ML/ha = 120 mm

Application efficiency (Ea) = 70 ÷ 120 = 58.3%

Overhead irrigation

Soil moisture deficit before irrigation = 70 mm

Soil moisture deficit after irrigation = 30 mm

Water delivered to rootzone = 70 – 30 = 40 mm

Total water applied = 40 mm

Application efficiency = 40 ÷ 40 = 100%

Note that this calculation of application efficiency does not account for losses such as wind interception or evaporation. For overhead sprinkler systems, these losses are less than 5% (see WATERpak chapter 5.5) and are extremely difficult to measure. For surface irrigation systems, evaporation from furrows is extremely small and also very difficult to measure.

Where tailwater recycling is practiced, the field application efficiency is effectively increased by reuse of this irrigation water. It is important to calculate a volumetric efficiency of the tailwater return system to be incorporated into the application efficiency term, particularly if a farm irrigation efficiency is to be calculated (see below). Confusion will be minimised if the method of handling tailwater is briefly defined.

Furrow irrigation with tailwater recycling

Soil moisture deficit before irrigation = 70 mm

Soil moisture deficit after irrigation = 0 mm

Total water applied = 1.2 ML/ha = 120mm

Tailwater available for reuse = 25 mm

Net water applied = 120 – 25 = 95 mm

Application efficiency (Ea) = 70 ÷ 95 = 73.7%

Here the volume of tailwater available for re-use is not equal to the amount of tailwater actually leaving the field. In this case, 0.3 ML/ha of water left the field as tailwater, but following distribution losses before reuse, only 0.25 ML/ha (85%) was subsequently available. The application efficiency has been appropriately modified by including the net water application (water applied minus water available for subsequent use).

Field Canal/Conduit Efficiency (E_b)

The field canal/conduit efficiency effectively covers the on-farm distribution system. The terminology 'Distribution Efficiency' is not used because it is typically reserved to describe the efficiency of the whole distribution system, from the headworks to the field (i.e. it includes river, irrigation scheme and on-farm distribution systems). Similarly, the term E_c is already in use for describing the conveyance efficiency of irrigation schemes, so the term E_b is the industry standard.

Field canal/conduit efficiency relates the water received at the field inlet to the water received at the farm gate; hence, it is usually accounts for losses in all components of the on-farm distribution system including storages and channels.

$$E_b = \frac{\text{water received at field inlet}}{\text{water received at the inlet to a block of fields (farm)}}$$

The same methodology of comparing water input to water output can be applied to the individual components of the on-farm distribution system (such as individual storages or channels) and is discussed further in WATERpak Chapter 1.6.

Farm Efficiency (E_f)

The use of the Application Efficiency (E_a) and Field Canal/Conduit Efficiency (E_b) terms allows a 'nested' approach for calculation of the Farm Efficiency. In other words, the farm efficiency is the product of the other efficiency terms:

$$E_f = E_a \times E_b$$

$$E_f = \frac{\text{irrigation water available to crop}}{\text{water received at field inlet}} \times \frac{\text{water received at field inlet}}{\text{water received at a block of fields (farm)}}$$

So:

$$E_f = \frac{\text{irrigation water available to crop}}{\text{water received at a block of fields (farm)}}$$

Calculating farm efficiency is useful for determining the potential for water savings, but it is not possible to establish where these savings can be made. Determining efficiency at the field scale is more useful for assessing the potential management or infrastructure changes that should be made. The nested approach for calculating efficiencies also means that once any two of the efficiency terms (E_a, E_b or E_f) are known, the other can be deduced.

Estimating farm irrigation efficiency

In practice, calculating whole farm irrigation efficiency can be complicated. To start with, there are likely to be many fields, and the irrigation water available to the crop needs to be determined for each irrigation and for each field. Furthermore, tailwater recycling complicates the calculation of farm efficiency, and it may be confusing to try and apply the nested approach.

However farm irrigation efficiency can be estimated through the process of water accounting. Water accounting is a process of tracking irrigation water and estimating the proportion of this water that is actually used by the crop across the entire farm. The result gives a benchmark of farm management, indicates the performance of water, and identifies the potential for water savings and maximisation of economic returns. This process accounts for rainfall and evaporative demand and results in an estimation of the farm efficiency, which can be used to compare between properties, regions or seasons.

From the formula for farm efficiency given above, we need to know the amount of irrigation water available to the crop and the amount supplied to the farm. The amount of irrigation water actually used by the crop, evapotranspiration or ET_c (WATERpak Chapter 2.8), is often used to help determine the amount of water available to the crop from irrigation. This is only an estimation of the water available to the crop, because the irrigation system may efficiently deliver water that the crop does not use for some other reason (e.g. disease). However it should be sufficient for most purposes.

Working out the proportion of irrigation water used by the crop involves starting with the crop's total water use (ET_c), subtracting the effective rainfall (RE) and accounting for the difference between the soil moisture at planting and the soil moisture at harvest (ΔSM). In this way, we have subtracted that water which was not supplied by irrigation from the crop's total water use.

$$\text{Irrigation water available to crop} = ET - RE - \Delta SM$$

Working out the amount of irrigation water supplied to the farm is somewhat easier and involves accounting for water from all sources:

- River
- Bore
- Scheme
- On-farm Harvesting (not recycling)
- Water used from on-farm water storages (ΔSW).

$$\text{Water received at a block or fields (farm)} = \text{river} + \text{bore} + \text{scheme} + \text{harvested} + \Delta SW$$

Table 1.2.2 illustrates the water account for an irrigated farm over two seasons. The water inputs from different sources, crop water use and some important water use indices are presented in the example.

Table 1.2.2 – Water account for an irrigated farm over two seasons

Season	1996/97	1997/98
Production details		
Area grown (ha)	3064	3173
Total production (bales)	19234	25495
Average yield (bales/ha)	6.3	8
Water supply		
Total water pumped (bore)	0	1445
Total water pumped (river)	7447	12100
Total water pumped (ML)	*7447*	*13545*
On farm storage at planting (ML)	6250	6500
On farm storage at harvesting (ML)	3975	4473
Used from farm storage (ML)	*2275*	*2027*
On farm harvested (ML)	*3710*	*1402*
Water used on other crops (ML)	*2300*	*2800*
Total irrigation applied on cotton (ML) = total pumped + used storage + harvested – other crops	11132	14174
Rainfall		
In season rainfall (mm)	518	459
Run-off (mm)	171	159
Effective rainfall estimate (mm) = (rainfall – run-off)	*347*	*300*
Estimated effective rainfall for farm (ML) = (Effective rainfall (mm) ÷ 100) × area (ha)	10632	9519
Rainfall efficiency (%) = effective rainfall ÷ total rainfall	67	65
Soil water		
Used soil reserve (mm) average of all fields (soil moisture at sowing – soil moisture at harvest)	119	133
Used soil reserve ML = (Used soil reserve (mm) ÷ 100) × area (ha)	3646	4220
Total seasonal water usage (ML) = total irrigation + effective rainfall + harvested water + used soil reserve	25410	27913

Water use summary		
ML/ha pumped	2.42	4.03
ML/ha effective rainfall	3.47	3
ML/ha harvested	1.21	0.44
ML/ha used soil reserve	1.19	1.33
ML/ha total water usage	8.3	8.79
Total seasonal crop water use (ET) mm	690	772
Water use indices		
Crop water use index (kg/mm/ha)	2.06	2.36
Crop water use index (bales/ML) = yield ÷ ET	0.91	1.04
Production WUI (farm) (bales/ML) = yield ÷ total water (with effective rain)	0.76	0.91
Irrigation WUI (farm) (bales/ML) = yield ÷ irrigation water	1.73	1.8
Farm irrigation efficiency		
Irrigation water used in ET (mm) = ET – effective rainfall – ∆soil moisture	226	343
Irrigation water used in ET (ML) = (mm) × area (ha) ÷ 100	6924	10883
Whole farm irrigation efficiency (%) = irrigation water used in ET ÷ total irrigation water	62	77

Such water accounting has been made significantly easier in recent years by software such as Watertrack™ (see below) which can calculate crop water use for each field, track losses through each irrigation system component and accurately calculate farm efficiency.

Uniformity

Uniformity is a measure of how evenly water has been applied to a field and is expressed as a percentage (%). It is only applicable at the field scale. Low uniformity results in parts of a field being under-watered and/or over-watered, which can result in poor crop uniformity and waterlogging. The standard calculation of uniformity is called Distribution Uniformity (DU) and compares the lowest quarter of infiltrated depths to the average of all infiltrated depths

$$\text{Distribution uniformity (DU)} = \frac{\text{Average of lowest 25\% of infiltrated depths}}{\text{Average of all infiltrated depths}}$$

Some irrigation system types, such as drip and centre pivot, have different uniformity measures that are more appropriate for their specific characteristics. These indicators and the methods for obtaining measurements are detailed in WATERpak chapters 5.5 and 5.6.

Calculating distribution uniformity for furrow-irrigated fields typically requires computer simulation, because it is otherwise not practical to obtain the depth of infiltrated water at a sufficient number of points down the field. WATERpak chapter 5.3 has more information on determining DU for surface irrigation fields.

Irrigation Benchmarking

Benchmarking is a process by which a comparison is made between practices, processes or performance indicators. Irrigation benchmarking most typically takes the form of performance benchmarking; that is, comparing performance indicators such as WUI. Performance benchmarking is useful to gauge historical performance but is not particularly good at identifying pathways to best practice.

On the other hand, process benchmarking involves comparing the processes of one business with those of another, that is regarded as demonstrating 'best practice'. In this case, performance benchmarking is often a first step to identify the best practice business, but then a much deeper comparison of the processes and decisions that result in this high performance is undertaken.

For the purposes of this discussion, we will concentrate on performance benchmarking. However the value of process benchmarking should be recognised by those who wish to meaningfully improve their performance.

When undertaking irrigation benchmarking, there are no set rules to suggest what data to compare or what it could be compared to. You might want to compare the amount of water you applied this year to the amount applied last year for example.

However, some comparisons are going to be more useful than others. A good example is when comparing between different regions if you don't take rainfall into account, then you will not get a very good comparison.

Calculating recognised water use indices and irrigation efficiencies will give you a standard calculation which can then be compared spatially (to another field, another farm, another region, another country) or over time (season, years). The advantage of using standard performance measures is to ensure meaningful comparisons.

Some benchmarking examples:

- Comparing the performance of different farming enterprises, for example the growers in a local area
- Compare the performance of a single field over a period of 3 seasons, to see if management changes are having a positive effect
- Comparing the performance of your enterprise to industry averages or targets
- Comparing performance within a farm, for example between a number of adjacent fields, to determine which need additional work to increase their performance and bring them 'up to scratch'

It is typical for benchmarking to be undertaken on a number of individual farm elements (e.g. fields, storages, distribution system, etc.) as well as for the whole farm. There are a number of reasons for this, which are summarised below.

Whole Farm

Advantages	Drawbacks
Includes all water and production	Includes all losses – does not distinguish between where water losses or low production occurs
Good for comparison between enterprises	Does not identify the individual areas that need attention
May be easier to obtain data for the whole farm	
Able to relate production to water use (WUI's) for the whole farm	WUI's calculated include all losses – not just those within fields

Individual Elements (e.g. Field, Storage, Channel)

Advantages	Drawbacks
Gives greater information that can be used to guide management decisions	Requires more detailed inputs which can be more difficult or expensive to obtain
Can provide a wealth of internal information	The amount of information can be time consuming to analyse
Can still allow comparison with external benchmarks for individual irrigation system elements	Calculation methods (i.e. for WUI's) must be standardised to allow meaningful comparison.
	The large number of different indices can be confusing (e.g. rainfall/no rainfall, effective rainfall/total rainfall, tailwater included/not included)

Fields

- Figures can be calculated using outflow (tailwater) to give more accurate figures, however accounting for the loss of tailwater during recycling usually requires estimation or use of a comprehensive farm water model such as WaterTrack™.
- Calculating Application Efficiency accurately for surface irrigated fields requires detailed modelling (Irrimate™)
- Calculating Distribution Uniformity for surface irrigated fields also requires Irrimate™
- Further information can be found in WATERpak Chapter 5.3
- As there is often little or no drainage or runoff from drip or sprinkler irrigated systems, calculation of application efficiency requires accurate measurement of evaporative losses and remains a detailed research task.
- Calculation of uniformity measures for sprinkler or drip systems is undertaken using catch cans or by measuring flow and pressure of individual emitters.

Storages, Channels

- Requires inflow and outflow to calculate storage or distribution efficiencies
- Indices are not appropriate as there is no production output
- To determine whether losses are due to seepage or evaporation requires more detailed measurement (e.g. storage meter, storage survey, WaterTrack™)
- Further information can be found in WATERpak Chapter 1.6

Calculating Benchmark Figures

Methods for calculating benchmark figures can vary depending upon the complexity of your irrigation system and the type of benchmark being calculated. For example, the process above for determining whole farm efficiency is a reasonably complicated procedure that is probably best undertaken using a specialist software tool. On the other hand, determining simple water use indices such as IWUI and GPWUI for an individual field is generally much simpler and could be undertaken by hand.

Table 1.2.2 provided a template that could be applied to most basic calculations. This template involves:

- recording the yield and area under consideration;
- recording the water supplied to this area from the relevant sources required for the indicators to be calculated (irrigation water, rainfall, effective rainfall, soil moisture, etc.); and,
- determining the required indicators.

The simplest of these calculations could be undertaken by hand or using a spreadsheet. A simple whole farm calculator which follows this format is available online to undertake the basic farm scale water use index calculations. However none of these methods assist with determining any of the difficult to estimate input parameters such as effective rainfall or crop water use.

Some tools can assist with determining some of these input parameters. For example, tools such as CropWaterUse and Hydrologic can calculate crop water use and basic field scale water use indices.

However there are few full water accounting packages that can account for the necessary inputs at the field scale and aggregate them to the farm scale, especially for the type of surface irrigation systems utilised in cotton growing regions. Watertrack™ is one such package which not only determines input parameters such as crop water use and effective rainfall but also allows you to determine benchmark figures for individual storages, channels and fields as well as for the whole farm.

Comparing Benchmark Figures

Benchmark figures can be compared internally and externally, between different fields or regions and across seasons. However, it is important to understand what each indicator is most useful for, so that comparisons are credible.

- Irrigation Water Use Index (IWUI) does not include rainfall.
  - IWUI is useful for comparing between nearby fields or farms in the same season
  - Comparing over significant distances or between seasons can introduce variability due to differences in rainfall.
- Gross Production Water Use Index (GPWUI) includes rainfall.
  - The rainfall component can be either total or effective and should be specified as such.
  - GPWUI is more useful for comparing between seasons and across regions but does not reflect the proportion of total water contributed by irrigation.
- Crop Water Use Index (CWUI) includes only the water used by the plant (ET_c).
  - It does not include the total water applied (whether this is from rainfall or irrigation)
  - Hence it is possible to apply significantly more water than necessary and still obtain a reasonable CWUI.
  - CWUI is really a crop performance measure, not an irrigation performance measure and variations in CWUI may be due to, for example, variety, nutrition, climatic variables, timing of water application.
  - For a definition of CWUI see WATERpak Chapter 2.1.

Because of these differences, it is suggested that a suite of indicators is used for comparison. In particular, it is recommended that both IWUI and GPWUI should be used when benchmarking. This allows the regional or seasonal differences in evaporative demand or rainfall that are included in the GPWUI to be accounted for in the comparison. If IWUI were to be used in isolation for such comparisons, such differences could be mistaken for poor irrigation system performance.

Internal comparison is reasonably simple to facilitate, by determining indicators across a range of irrigation system components and recording these over time. However to compare your benchmark figures externally there are a number of options:

- You may decide to compare informally with your neighbours
- You may compare data formally through existing economic benchmark groups.
  - If you are part of a benchmark group and would like them to include standardised water use benchmarks, please discuss this with your local Irrigation or Water Use Efficiency Officer
- Your consultant may like to coordinate a benchmark group amongst their client base.
  - Again, your industry extension officer can help to establish this process.
- Some benchmark figures exist from previous research studies.
  - Chapter 1.3 of WATERpak contains some historical benchmark data for the cotton industry.

Note that the extent and accuracy of on-farm water measurement has increased significantly in the last five years, and will continue to do so. This is important to remember as benchmark figures calculated in historical studies may be less accurate. The availability of increasingly accurate benchmark data will improve as more growers undertake coordinated benchmarking studies

Water Budget

A water budget is used to determine how best to use the available water resource. A water budget is often quite different to a budget prepared for other inputs such as fertiliser, as the water budget is used to partition a limited resource (water) where the availability of the resource may vary significantly during the season due to rainfall.

Because of this, a water budget will always include risk based decisions.

A water budget has two main purposes:

- To determine what area of crop should be planted for the water resource available at the beginning of the season.
- To determine how to best utilise crop inputs during the season as water availability changes (includes determining when to plough out crops due to insufficient water availability).

Some things to take into account:

- The seasonal water requirements for your crop (benchmark data or crop ET calculation).
- Historical median rainfall.
- Probability of above or below median effective rainfall (seasonal forecast).
- Typical and/or forecast rainfall timing. Will this affect irrigation, dam supplies, or extraction limits?
- Ability to adjust crop water availability without jeopardising yield or quality?
- Available water supply (e.g. flow rate, on-farm capture, total storage capacity, trading)
- Acceptable risk level
- Economics (is it better economically to fully irrigate a smaller area, or partially irrigate a larger area?)
- Available Tools (e.g. CropWaterUse, CottBASE, Whopper Cropper, WaterTrack)

We may 'predict' whether the season will be wetter or dryer than the median year and plan accordingly by investigating the climate, past rainfall records, and current climatic patterns (for example SOI and El Niño). By making a decision on the contribution of rain, we are allocating risk.

For example, a low risk decision would be to plant only the area for which you currently have enough water. However, this would limit the opportunities presented by significant in-season rainfall and water capture.

Information on climate variability and records of climatic data may be found at the Bureau of Meteorology website or your local Irrigation or Water Use Efficiency officer may be able to help. Further information on risk and decision making is included in WATERpak Chapters 2.2 and 3.3.

Water Budget vs. Water Budget Irrigation Scheduling

Some people refer to the process of scheduling irrigation based upon a balance of soil water inputs (irrigation & rainfall) and outputs (ET, runoff, drainage,) as 'water budget scheduling'. A better name would be water balance scheduling or soil water accounting. This process is covered in WATERpak Chapter 2.1 and should not be confused with the preparation a water budget.

Budgeting Methodology

The maximum area of crop that can be irrigated is determined by the crop water requirements, the irrigation system capacity and efficiency, and the availability of water.

$$\text{Area} = \frac{\text{irrigation water available}}{\text{annual crop water requirement} \times \text{irrigation system efficiency}}$$

For example:

A cotton crop in Southern Queensland might require about 900 mm (9 ML/ha) of water. Historical figures indicated that the median rainfall during the season for this location is 350 mm (3.5 ML/ha). So for a median year the irrigation requirement is 5.5 ML/ha.

At planting, the grower has 300 ML in storage and 700 ML of available allocation. The grower estimates that another 500 ML will be harvested during the season.

Irrigation water available: 1500 ML

Irrigation requirement: 5.5 ML/ha

Whole Farm Efficiency: 64%

$\text{Area} = 1500 \div 5.5 \times 0.64 = 175 \text{ ha}$

Your seasonal crop water use can be estimated in a number of ways. The simplest method is to use one of the available tools such as CropWaterUse which will allow you to calculate the crop water requirements. Alternatively, you could use benchmark crop water use figures from previous seasons. However, be careful; if you base your crop requirements on IWUI calculated at the farm scale, your water losses will have already been taken into account and hence you do not need to include the system efficiency in the above calculations.

Water budgeting tools

A number of tools can be used to help produce a water budget. For example, crop modelling tools such as CottBASE and WhopperCropper can be used to predict likely yield given different conditions and available water inputs.

From these predictions, you can choose an amount of water to allocate to each field in order to maximise your yield or economic return.

This enables you to compare different scenarios of water availability in terms of final yield, as illustrated in Figure 1.2.3. The 25th and 75th percentile figures are used to indicate the likely range of values that might be expected.

Figure 1.2.3 – CottBASE comparison of predicted yield for multiple scenarios of available irrigation water

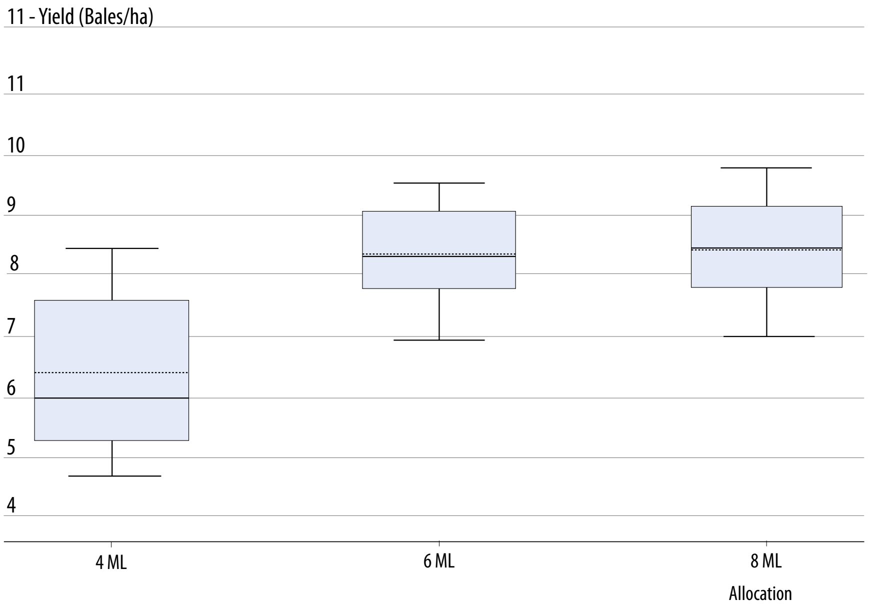


Table 1.2.3. An example method for comparing the economics of various irrigation allocations using data from CottBASE

Allocation	TOAL	Cotton Area	Yield (Bales/ha)			Range	Total Bales		
ML/ha	(ML)	(ha)	25%	Average	75%	Bales / ha	25%	Average	75%
4	1000	250	5.2	6.4	7.6	2.4	1300	1600	1900
6	1000	167	7.7	8.4	9.1	1.4	1283	1400	1517
8	1000	125	7.7	8.5	9.1	1.4	963	1063	1138

Return @$400/bale			growing costs	Total	Gross Margin ($)		
25%	Average	75%	$ / ha	Cost ($)	25%	Average	75%
$520,000	$640,000	$760,000	$2,268	$567,000	-$47,000	$73,000	$193,000
$513,333	$560,000	$606,667	$2,520	$420,000	$93,333	$140,000	$186,667
$385,000	$425,000	$455,000	$2,800	$350,000	$35,000	$75,000	$105,000

These particular tools also allow the SOI (Southern Oscillation Index) phase to be taken into account, which means that the potential for different seasonal conditions can be taken into account when making decisions. In the example above, this means that it would be possible to determine the optimum amount of irrigation water to allocate for crops given the current SOI phase. Further examples of this functionality are included in WATERpak Chapter 2.3.

WaterTrack Optimiser™ is another very powerful tool that can be used to budget irrigation water. WaterTrack™ does not predict yield like CottBASE or WhopperCropper, but it does model each element of the irrigation system to quantify losses and produce benchmarking reports. In prediction mode, it can use historical climate data to predict when irrigations will occur, how much water will be used, what the losses will be, and when insufficient water is available.

As predictions can be performed at any time before planting or during the season, this tool is an extremely useful way to verify if you will be able to irrigate the proposed cropped area and to refine your water budget given the actual weather patterns experienced as the season progresses.

It would even be possible to use this tool to help make key decisions such as purchasing extra water, ploughing in a crop or assessing infrastructure changes or capital investments such as increased farm area, more or fewer storages, and deeper storages.

Figure 1.2.4 shows an example output report from WaterTrack Optimiser™ which predicted the dates at which insufficient water was available on-farm. In this particular example, an extra 235 ML was required. This prediction utilised weather data from a known dry year, so the grower could make a decision to accept this risk and hope for extra rainfall, or to decrease the area planted. Further simulations can be run during the season with updated weather records to modify management decisions if necessary.

Figure 1.2.4 - Watertrack water availability report that can be used for water budgeting.

WATER AVAILABILITY REPORT

From: 2/9/05 To: 5/3/06

Date	Farm Object	Overdraw (ML)
29/1/06	Inflow 54	18
1/2/06	Inflow 54	6
15/2/06	Inflow 54	77
16/2/06	Inflow 54	79
17/2/06	Inflow 54	49
18/2/06	Inflow 54	6
	Total Overdraw:	**235**

Notes:
The first overdraw of water occured on 29/1/06. At the end of the period there is a total overdraw of 235 ML.

Further Information

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1.3 Water use efficiency in the Australian cotton industry

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Key points

- Irrigation Water Use Index within the Australian Cotton industry has improved by 8 per cent per annum since 2000-01.
- Industry data suggests an average IWUI of greater than 1.5 bales/ML. There is however, significant farm to farm, and seasonal variability in this figure.
- The greatest water losses on farm are evaporation losses from on-farm storages – measurements from 30 farms suggest an average loss of 25 per cent but losses can be as high as 45 per cent
- The application efficiency of surface irrigation ranges from 65 to 90 per cent where tailwater recycling is used, averaging 76 per cent.
- Surface irrigation application efficiency could potentially be improved from 76 to 85 per cent as determined from simple management changes to 476 sub-optimal measured irrigation events.
- Despite the significant gains made in irrigation performance and industry WUE in the past decade, there remains scope for further improvement by irrigators at the lower end of the WUE ranges identified.

More than 98% of the water absorbed by the roots of any crop is transpired as water vapour during the course of plant growth. Most of this water is lost through stomata, which are specialised pores on leaf surfaces that allow water vapour to exit the leaf while carbon dioxide enters. This exchange process is necessary for photosynthesis and to maintain canopy temperature. Therefore, any measures to reduce water loss through the leaves (reduce transpiration) will also reduce photosynthesis and overall crop yields.

Water for growth is provided by rainfall or irrigation, but in both cases the amount of water supplied is rarely exactly the same as that required due to the timing and quantity of applications. Therefore the crop uses only a portion of water applied from rainfall and irrigation during the growing season.

In irrigation systems, the proportion of irrigation water actually used by the crop can be maximised by improving irrigation management and system design. These improvements in efficiency are important to save irrigation water, as well as to protect the environment.

Because the objective of applying irrigation is to produce yield, crop management such as fertiliser use, pest management, variety choice and tillage also has the potential to impact on water use efficiency.

Water use efficiency (WUE) is a generic term that covers a range of performance indicators that can be used to describe how efficiently water is used within the cropping system. The WUE performance indicators can be grouped into:

- Water Use Indices (relating crop production to water use)
- Irrigation system efficiency (relating water inputs to water outputs within the irrigation system)
- Distribution uniformity (a measurement of the evenness of irrigation application)

A full explanation of WUE is provided in WATERpak Chapter 1.2.

The Australian industry in summary

There have been a range of studies undertaken in the past 15 years aimed at quantifying the WUE of irrigated cotton production. These include:

- Cameron Agriculture and A.B. Hearn (1997) who collated data from Australian Bureau of Statistics (ABS), Department of Land and Water Conservation, NSW and Department of Natural Resources in Queensland. In addition they collected farm level and field level data from eleven farms in the Macquarie, Namoi, Gwydir and Macintyre valleys.
- Tennakoon and Milroy (2003) collected historical water management data at field and farm level from 25 farms in major cotton growing valleys for the 1996/97, 1997/98 and 1998/99 seasons.
- Dalton, Raine and Broadfoot (2001) from the National Centre for Engineering in Agriculture (NCEA), University of Southern Queensland surveyed eight farms within the Queensland-New South Wales Border Rivers catchment over the 1998-2000 cotton seasons. The data collected was used to calculate on-farm irrigation efficiency benchmarks.
- Between 1999 and 2003 the Queensland Rural Water Use Efficiency Initiative (RWUEI) collected annual data from up to twenty-nine benchmarking sites across Queensland in order to calculate WUE indices
- Harris (2012) summarised water productivity data from ABS and the Australian Cottongrower, together with industry studies during the past decade
- Montgomery and Wigginton (2012) summarised data collected from benchmarking studies at the farm scale across the industry in 2006-07, 2008-09, 2009-10 and 2010-11.
- Montgomery (2012) collected WUE benchmark data from 24 irrigated wheat farms from the 2008 season.
- Gillies (2012) has summarised the analysis of 542 surface irrigation performance evaluations conducted in the past decade. These events have been collated into ISID, a secure database which is accessed through the internet.
- Wigginton (2011) benchmarked the whole farm water balance for 30 farms within the Queensland Murray Darling Basin in the 2009-10 and 2010-11 seasons.

At the broad industry scale there has been an upward trend in Irrigation Water Use Index (IWUI) as a result of improved genetics and crop management, combined with improved irrigation practice (see Figure 1.3.1).

Figure 1.3.1 Irrigated cotton productivity (bales/ML of applied irrigation water) (Harris, 2012)

Table 1.3.1 - WUE Indices within the Australian cotton industry for the last 15 years.

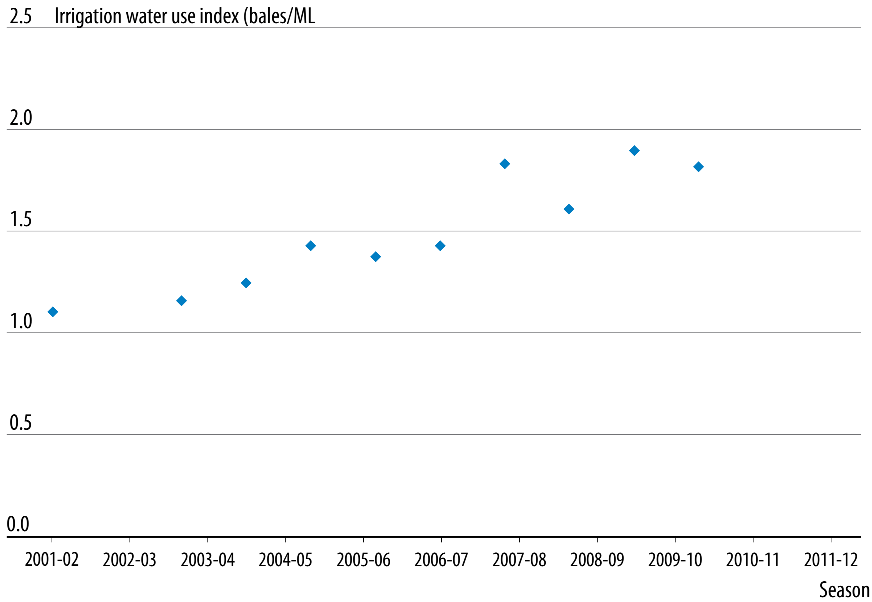
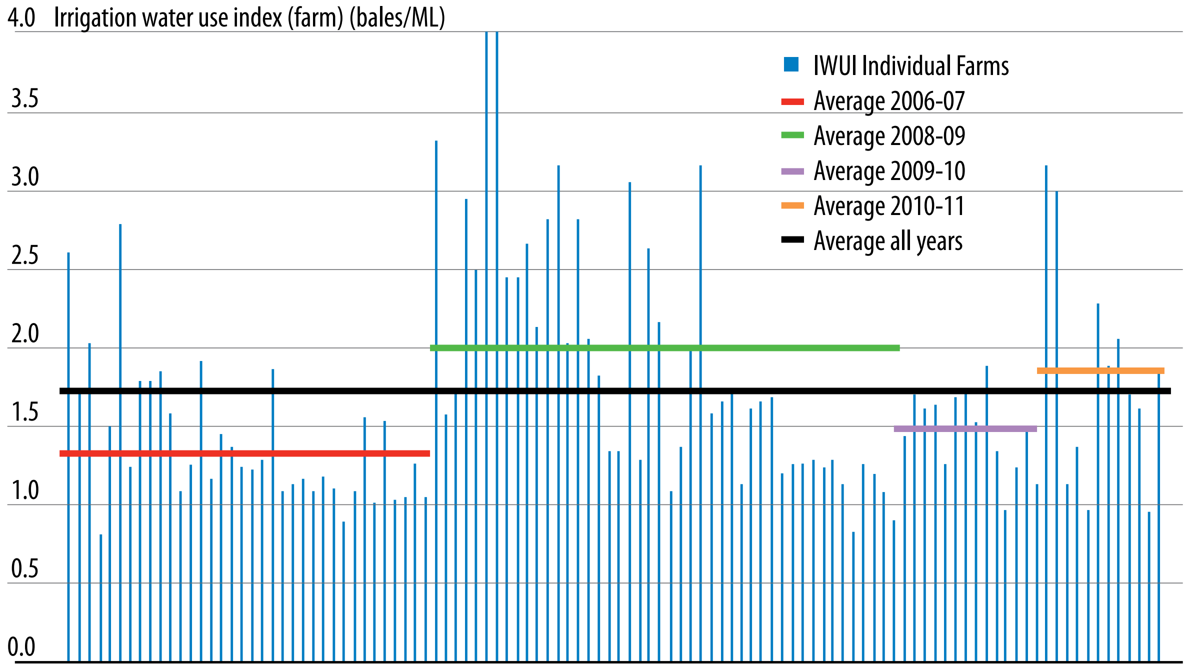


Table 1.3.1 summarises the results for cotton industry WUE indices collated by different projects over the last 15 years. The data here clearly shows the improvements in yield that have occurred, and these are reflected in the improved WUE indices presented (an improvement of 8 per cent per annum).

Project	Seasons	Region	No of farms	Irrigation ML/ha	Yield Bales/ha	IWUI bales/ML	GPWUI (farm) bales/ML
Cameron & Hearn	1988–89 to 1994–95	NSW & Qld	11	5.37	6.73	1.11	0.75
Tennakoon & Milroy	1996–97 to 1998–99	NSW & Qld	25	6.96	7.96	1.25	0.74
RWUEI Project	2000-01 to 2002-03	Qld	29	7.51	8.71	1.62	0.95
Montgomery	2006-07	Hillston to Emerald	37	8.17	10.7	1.31	1.13
Montgomery	2008-09	Hillston to Emerald	46	5.38	10.6	1.97	1.14
Wigginton	2009-10	Condamine & Lower Balonne	15	6.26	9.2	1.47	0.93
Wigginton	2010-11	Condamine & Lower Balonne	12	5.60	10.3	1.84	0.94

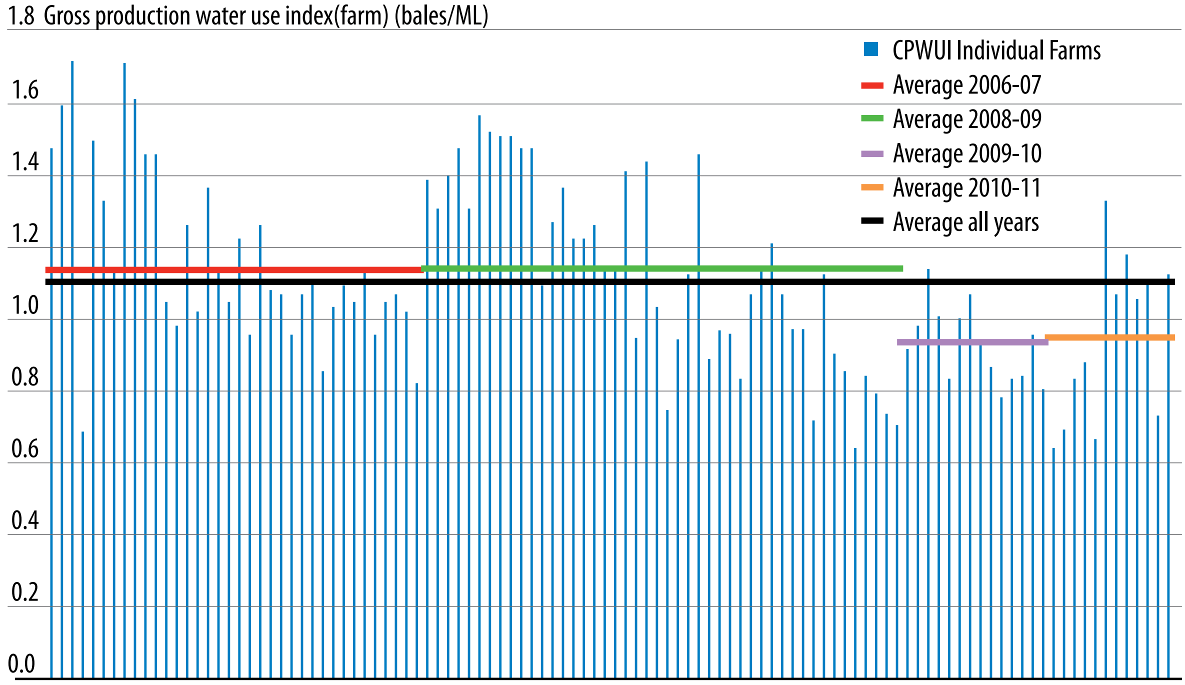
Individual farm WUE data is of particular interest as this can clearly demonstrate the potential for high IWUI (Figure 1.3.2) and Gross Production Water Use Index (GPWUI) (Figure 1.3.3) that can be obtained in irrigated cotton farming systems. However, this data also demonstrates the variability in these indices across farms and seasons.

Figure 1.3.2 - Irrigation Water Use Index (IWUI) for each individual farm



(Source: Montgomery and Wigginton, 2012)

Figure 1.3.3 - Gross Production Water Use Index (GPWUI) for each individual farm



(Source: Montgomery and Wigginton, 2012)

Measurements by Dalton et al (2001) showed that the greatest water losses reflected in whole-farm WUE are likely to be from farm storages. Evaporation losses can be as high as 10 mm per day resulting in storage losses of up to 50% over twelve months.

Seepage from unlined distribution channels vary with soil type and have been recorded between 1 and 23 mm per day. Storage and conveyancing losses are likely to be lower for bore supplies, although if bore capacity is limited, water would be pumped into storages prior to irrigation and potentially lost.

The more recent work by Wigginton (2011) confirmed the importance of evaporation losses from storages within the irrigated farming system. The average storage losses across the 30 farms evaluated accounted for 25 per cent of all farm water. The largest individual storage loss measured was 45 per cent of all farm water. For most storages, evaporation is the largest source of water loss, and this is typically between one and two metres per year if the storage contains water all year round.

The other important aspect in improving whole farm WUE is improving application efficiency. Analysis of 542 surface irrigation evaluations within the Irrimate Surface Irrigation Database (ISID) by Gillies (2012) is summarised in Table 1.3.2. This data includes evaluations undertaken in all major cotton growing catchments from 2000-01 to 2011-12. They represent irrigation performance under normal grower management.

Table 1.3.2 - Summary of ISID results (542 events)

	Average	1st Quartile	Median	3rd Quartile
Flow rate (L/s per 2m width)	4.4	2.9	3.8	5.6
Run time (hours)	12.6	8.6	11.6	14.8
Total water applied (ML/ha)	1.36	0.96	1.2	1.56
Application efficiency (%)				
- without tailwater recycling	64.6	53.3	6.46	77.5
- with tail water recycling (%)[1]	76.3	64.7	79.5	90.4
Infiltration (mm)	108.9	76.9	98.9	126.8
Deep drainage (mm)	28.4	3.4	16.6	41.4
Runoff (mm)	26.5	7.6	17.9	32.6

(Source: Gillies, 2012) [1]Assumes that 85 per cent of the tail water is recovered.

The application efficiency reported in Table 1.3.2 is defined as the percentage of total water applied that is added to the root zone storage and can be used by the crop. A more meaningful value for the majority of growers is the application efficiency with tailwater recycling which takes account of the runoff that can be recaptured for future use. Industry studies have shown that tailwater system losses are generally less than 15 per cent.

The data in Table 1.3.2 shows the average application efficiency of surface irrigation to be 75 per cent (with tailwater recycling, which is common practice within the cotton industry). It also shows the range in measured application efficiencies indicating the potential to further improve performance through management changes. The changes most commonly used have been changes in siphon flow rates and cut-off times to optimise irrigation performance. The value of these practices is summarised in Table 1.3.3 which compares the measured and predicted performance possible through these changes on 476 events reported in the ISID database.

Figure 1.3.3 - Improvement in irrigation performance through adoption of recommended flow rates and cut-of times (476 events)

	Measured (average)	Optimised (average)
Flow rate (L/s per 2m width)	4.4	5.8
Run time (hours)	12.7	8.4
Total water applied (ML/ha)	1.42	1.16
Application efficiency (%)		
- without recycling	63.7	72.6
- with recycling	75.6	84.8
Infiltration (mm)	113.1	97.7
Deep drainage (mm)	30.4	15
Runoff (mm)	28.2	18.4

(Source: Gillies, 2012)

The data in Table 1.3.3 shows that, on average, application efficiency improvements of 10 per cent were possible for these events, with a halving of the volume of water lost to both deep drainage and runoff. Assuming that 85 per cent of tail water is recycled this equates to a water saving of 0.17 ML/ha per irrigation event.

Conclusion

There have been significant improvements in irrigation management within the Australian cotton industry over time, which is reflected in the broad improvement in IWUI values presented in Figure 1.3.1. Data collected at the farm and field scale provide further evidence of this.

However the data also shows that there is still a range of irrigation performance within the industry. This suggests that there is still significant scope for producers at the lower end of the range to increase the efficiency with which they use water.

Collecting water management data at the field and farm level provides important information for the diagnostic analysis of water use efficiency and the opportunity to further improve irrigation performance.

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1.4 Understanding deep drainage

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Key points

- Deep drainage below the root zone causes rising watertables and salinity and can be significant even in heavy clays.
- Drainage occurs when more rain or irrigation is added to soil than there is empty storage capacity to hold it.
- Drainage risk can be reduced by maintaining sufficient empty storage (soil water deficit) as a buffer.

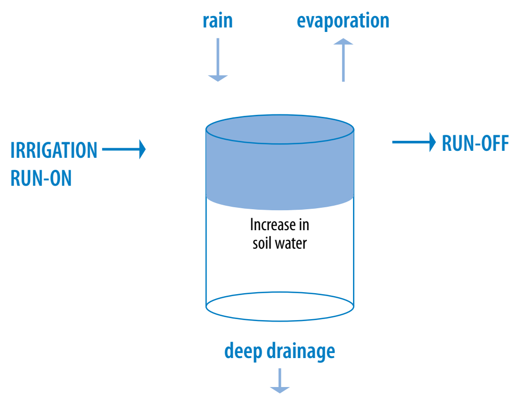
What is deep drainage?

When water in the soil moves below the root zone it is irretrievably lost to plants and is referred to as **deep drainage**. It is usually a small yet significant component of the soil water balance.

The soil water balance can be compared to the financial balance sheet of a company that balances funds credited to and debited from an account. The credits in the water balance are rainfall, run-on from upslope, and irrigation. On the debit side are evapotranspiration, run-off and deep drainage. The net profit or loss – the difference between the total credits and total debits – is analogous to the change in soil water storage. The water balance can be represented mathematically as:

However, there are important differences between a financial balance and the water balance. Net profit can accumulate over time and a bank balance can increase indefinitely. (Net losses can also accumulate indefinitely, so long as funds can be borrowed.) In the soil water balance, soil water storage is finite. It cannot be overdrawn, and the maximum storage is limited by the total porosity of the soil. This means that once the storage is full or empty, one of the other components on the right-hand side of the equation has to change. Another difference is that, while a bank account does not limit the rate at which funds are added to or withdrawn from it, the soil does limit the rate at which water enters or leaves it. If water is added too fast, run-off increases.

Rainfall + run-on + irrigation = evapotranspiration + run-off + deep drainage+ increase in soil water



Similarly, the rate at which water can move in the soil may limit evapotranspiration.

The water balance can be calculated over different time periods. Over short periods (days, months or seasons), the change in soil water can be an important component of the balance (see below), but over longer periods the change becomes negligible, because of the fixed amount of storage available.

The components of the water balance are usually quoted in units of depth per unit time, for example, mm/yr, or volume per unit area per unit time, for example ML/ha/yr. (Note that 1 ML/ha is equivalent to 100 mm.)

Why is drainage important?

In much of inland Australia, shortage of water is a major limitation to plant growth. Native ecosystems have adapted to this by ensuring they use most of the water entering the soil. As a result, deep drainage under native vegetation is usually close to zero. Crops and pastures generally use less water over the long term, resulting in increased run-off and deep drainage. In many cases in the past, it has been assumed that drainage in heavy clays is negligible because of their low hydraulic conductivity (e.g. Tennakoon and Milroy, 2003). However, research over the last decade in particular has demonstrated that deep drainage does occur, and in some circumstances can be a significant loss. This research is summarised in WATERpak chapter 1.5.

In dryland and especially in irrigated agriculture, drainage is a waste of a valuable resource and can remove nutrients from the root zone. Although it is often only a small fraction of the water balance (WATERpak Chapter 1.5), it disrupts the hydrologic cycle of the landscape, which has long-term consequences in the broader landscape.

In many inland regions of Australia, large amounts of salt have built up over geological time deep in the soil. In part this has happened because of the efficiency of native vegetation in using available water, which has prevented the tiny quantities of salt in rainfall from being leached from the soil. Instead, salts concentrate at the bottom of the root zone over thousands of years. In other situations, salt produced by the weathering of rock has built up due to the same lack of leaching. In yet other areas, groundwater occupies sedimentary rocks of marine origin.

When native vegetation is cleared, drainage generally increases, with two effects:

- Drainage can mobilise salt stored in the soil.
- Drainage can increase recharge to groundwater, causing a rise in groundwater levels if the groundwater cannot move fast enough to accommodate the extra recharge.

The rise in groundwater causes waterlogging in lower parts of the landscape. Where the groundwater contains either pre-existing salt or salt mobilised by extra drainage, salinity occurs as this salt is brought into the root zone. Waterlogging and salinity can occur at the site of increased drainage, but often occur elsewhere in the landscape. Therefore salinity has to be tackled at the landscape scale and requires cooperation between land managers in areas where salinity is occurring with those where drainage has increased.

How does drainage happen?

Principles of soil water storage and movement

Before discussing the mechanisms leading to drainage, it is worth describing the principles of water storage and movement in soil. Water is stored in and moves through pores in the soil. There are two basic principles that govern how pores hold and transmit water.

- The strength with which pores hold water – the 'suction' they can exert – is inversely proportional to their diameters. If the diameter is doubled, the suction is halved.
- The rate at which water moves through pores is proportional to the fourth power of their diameters (that is, diameter raised to the power of 4). If the diameter is doubled, the rate of water movement is increased 16 times.

The amount of water that the soil holds at saturation is determined by the porosity of the soil (although soil rarely saturates completely because of trapped bubbles of air). However, only a portion of the porosity can store water in a form available to plants. On the one hand, pores larger than about 0.03 mm in diameter cannot hold water against the influence of gravity and will eventually drain. They can only store water temporarily. The volume of such pores is referred to as the **drainable porosity**.

On the other hand, pores with diameters less than about 0.00002 mm exert such a high suction that plants are unable to extract it. Water stored in such pores is generally considered ‘unavailable’. Pores between these extremes hold water sufficiently strongly that it does not drain but not so strongly that it cannot be extracted by plants. The maximum volume of water that can be held in these pores is the **plant available water capacity** (PAWC). (see WATERpak chapters 2.1 and 2.5 for further explanation of soil water terms).

Because small pores exert greater suction than larger ones, water is stored in small pores more readily than in larger ones. In a wet soil only the largest pores are empty and the suction exerted by the soil as a whole is less than in a dry soil, in which small pores are also empty. Therefore a layer of dry soil tends to suck water from a wetter layer even against the influence of gravity.

Water moves through the soil under the influence of both gravity and ‘suction’. However, water moves much faster through large pores than through small ones. **Thus the ability of wet soil to transmit water – its ‘hydraulic conductivity’ – is much greater than that of dry soil**. Once the drainable porosity has emptied, the rate of water movement drops considerably.

Water balance basics

During rain or irrigation a portion of the water runs off, depending on the surface properties and slope. (This is called **infiltration-excess** run-off, as it is water in excess of the infiltration capacity of the soil surface.) The remainder infiltrates the soil and fills empty pore space.

In general, water fills the soil from the top down. As the surface layer fills, water moves to deeper layers under the influence of gravity. If the deeper layers are drier, the greater suction of those layers also assists water movement.

If the rate of water movement to deeper layers is insufficient to accommodate the infiltrating water, water backs up and extra run-off is generated: this is referred to as **saturation-excess** run-off. This can happen in texture-contrast soils in which a relatively porous topsoil sits above a relatively impermeable, clay subsoil. Water only moves into the subsoil slowly, so, once the topsoil has filled, extra run-off is generated if rain or irrigation continues.

In contrast to water input to the soil, which tends to occur in discrete rainfall or irrigation events, removal of water by evapotranspiration is a more continuous process. When the surface soil is wet, evaporation from the soil surface is determined by the evaporative demand of the atmosphere (radiation, temperature, relative humidity, wind, and other factors). However, once the surface has dried, its hydraulic conductivity drops rapidly and evaporation is limited by the rate at which water is able to move to the surface. Transpiration by plants is also controlled by evaporative demand, but they are able to extract water from wherever it is available within their root zone.

Water storage in the soil root zone can be viewed as a water tank that fills from the top down. The depth of the tank represents the depth of the root zone. The width of the tank can vary with depth and represents the way water-holding capacity can change with depth as soil texture, structure or bulk density change. Water added to the top of the tank represents the water that infiltrates after rainfall, irrigation or run-on. With every rainfall or irrigation event, the depth of water in the tank increases by the amount of water that infiltrates. Between rainfall events, evaporation or transpiration by plants removes water and the depth decreases.

The pattern over time is for the depth of stored water to fluctuate, with relatively rapid increases followed by periods of slower decline. Clearly, so long as the decline in depth between fillings creates sufficient empty storage to accommodate the next filling, the tank never completely fills and the depth fluctuates about an average. However, if the rate of emptying over a particular period is insufficient to match all the amounts added during the same period, water accumulates and eventually reaches the bottom of the tank. Any additional water results in leakage from the bottom of the tank, which represents deep drainage beyond the root zone.

The process described above is the most common form of drainage and is called ‘matrix drainage’, because water flows through the bulk (‘matrix’) of the soil. Another type of drainage occurs when water flows down large pores (macropores) all the way through the root zone, bypassing the soil matrix as it does so. This is called ‘bypass drainage’. For example, in Vertosols (cracking clay soils) the soil matrix has relatively small pores so it can only fill up slowly. During heavy rain or flood irrigation, the matrix is unable to fill up fast enough so water flows down cracks and other large pores directly to the subsoil (Ringrose-Voase and Nadelko, 2011).

Bypass drainage occurs when bypass flow occurs all the way through the root zone. For bypass flow to occur two conditions must be met. First, the soil must have macropores – pores larger than about 0.03 mm – that empty under the influence of gravity and rapidly conduct water to deeper layers. Most soil contains macropores created by cracking, the tunnelling activity of soil fauna or the packing of soil aggregates. However, for bypass drainage to occur the soil must have a network of macropores that allows bypass flow all the way through the root zone. Second, water must be supplied sufficiently rapidly that it is not simply absorbed by the soil matrix. When this happens water ponds on the surface. This condition only occurs during periods of heavy rain or during surface irrigation.

Because most soils contain macropores, bypass flow between soil layers within the root zone is reasonably common during heavy rainfall or surface irrigation. So long as bypass flow only occurs within the root zone it will not necessarily cause drainage, because plants can extract the water from whichever layer it ends up in. However, bypass drainage is only a common event in rare situations – surface irrigation of Vertosols being one of them – where the soil has a network of macropores all the way through the root zone and where water is frequently ponded on the surface

Factors affecting drainage

Matrix drainage occurs when the input of water from a rainfall or irrigation event is greater than the spare storage capacity of the soil. This spare capacity is referred to as the **soil water deficit** and equals the PAWC minus the amount of available water actually stored in the root zone.

Drainage does not occur continuously, but in episodes. On the one hand, small events only cause drainage if the deficit is already small. This might be because the PAWC is small or because the soil is already wet and nearly full. On the other hand, larger events are able to cause drainage even when the deficit is larger. The probability of a drainage event occurring is determined by:

- the size of rainfall or irrigation events
- the intensity of rain or irrigation relative to the infiltration properties of the soil
- the soil water deficit.

Size of the rainfall or irrigation event

The effects of the size of individual inputs of rain or irrigation on filling the water storage are self-evident. The size of rainfall events at a particular time of year is out of the control of the land manager, but additions of water by irrigation can certainly be adjusted to maximise water use efficiency and minimise drainage.

Apart from filling the available water storage, large inputs of water through heavy rain or surface irrigation that can cause ponding can also cause bypass drainage.

Infiltration properties

How much of any rainfall or irrigation event actually enters the soil is controlled by:

- slope. The steeper the slope, the less water infiltrates.
- soil surface properties. Surfaces with unstable structure crust easily, which decreases infiltration. This may be caused by silty texture, dispersive (sodic) clays or lack of organic matter. Compaction of the surface by machinery or animals can also decrease infiltration.
- cover by crop residues. Greater cover protects the soil surface from raindrop impact and improves infiltration.
- subsurface constrictions to water movement. These constrictions prevent water moving into the subsoil, causing surface layers to saturate more quickly and any additional rain or irrigation to run-off.

The role of infiltration properties in drainage is complicated. On the one hand, greater infiltration increases the probability of filling the available storage and causing drainage. On the other, infiltration needs to be maximised for plant production and to reduce the risk of soil erosion. In fact, poor infiltration can sometimes *increase* drainage, as when crops fail, leaving the land fallow and reducing the soil water deficit.

In general, land management should seek to maximise infiltration where possible. This can be achieved by:

- ensuring good cover through retention of crop residues, or sowing of sacrificial cereal crops;
- ensuring structural stability through maintenance of soil organic matter;
- avoiding surface or subsurface compaction by traffic.

Soil water deficit

To prevent deep drainage, the soil water deficit at a particular time of year needs to be large enough to accommodate the largest likely addition of water at that time of year. Otherwise, a large addition of water may fill the root zone beyond its PAWC and cause drainage.

The deficit acts as a buffer against rainfall and irrigation events. The larger the deficit, the greater the ability of the soil to absorb additions of rainfall or irrigation without drainage occurring. The deficit is controlled by:

- the water storage capacity of the soil
- the rate of accumulation of water over various time periods.

Soil water storage capacity: The storage capacity – the size of the 'tank' – is a function of the inherent water-holding capacity of each soil layer and the rooting depth – the width and depth of the tank, respectively. The main factors controlling these are as follows:

- Factors controlling the inherent water-holding capacity of each soil layer (see Figure 1.4.1):
  - soil texture – in general clay soils hold more water than sandy soil.
  - soil structure – compaction by traffic tends to reduce water-holding capacity
- Factors controlling the rooting depth (Figure 1.4.2):
  - vegetation species –trees and other perennial vegetation have greater rooting depths than annual species.
  - soil depth – rooting depth is limited by shallow soil or hostile soil conditions, such as alkaline or saline layers.
  - impeding layers – root growth is impeded by hostile layers due to soil texture, alkalinity or shallow saline watertables.
  - soil structure – compaction by traffic or depletion of organic matter can limit rooting depth, especially of annuals.

Water-holding capacity determines the maximum deficit size. For example, on a vertosol (cracking clay) it might be possible to completely buffer against drainage using pasture with relatively shallow roots, because the water-holding capacity of clay is so high. In contrast, deep-rooting tree species might be necessary on a lighter textured soil. The former situation is comparable to a wide, shallow tank and the latter to a thin, deep one.

Figure 1.4.1 The effect of soil texture on drainage

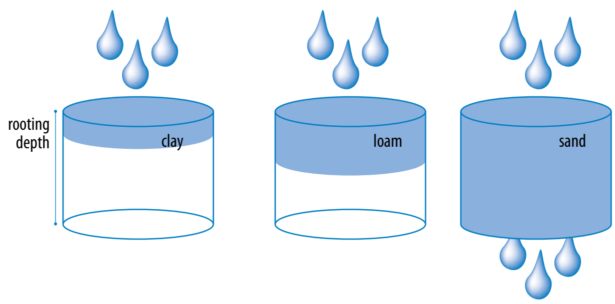
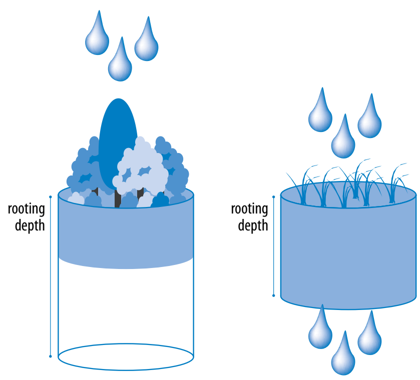


Figure 1.4.2 The effect of rooting depth on drainage



Rate of water accumulation: The size of the soil water deficit at a particular time of year or point in a crop rotation depends on the rate of accumulation of water in the soil profile. Over periods when inputs are roughly equal to losses by evapotranspiration, the deficit fluctuates about a mean (see Figure 1.4.3).

If this mean is large enough, drainage is unlikely, though not impossible if larger than average events occur close together. However, over periods when inputs are larger than losses (over-irrigation, for example), the deficit still fluctuates but gradually diminishes (Figure 1.4.4), with the likelihood of drainage increasing as it does so.

The factors controlling the accumulation of water are:

- climate
- crop vegetation management
- irrigation management.

Climate has a major control over the accumulation rate at different times of year. Total annual rainfall obviously affects the total input of water to the system. Within a region of broadly similar climate, wetter areas with greater rainfall and smaller potential evapotranspiration – for example, hills – tend to have a greater risk of drainage.

The distributions of rainfall and evapotranspiration through the year are also of great importance. There are two aspects: first is the evenness of rainfall through the year. Climates with more peaked rainfall distributions have greater drainage risk than those in which the monthly rainfall is more equal. Less water accumulates with an even distribution because there is more time between events to empty the storage.

The second aspect is the monthly distribution of rainfall relative to evapotranspiration. In southern parts of Australia, monthly rainfall and monthly potential evapotranspiration are out of phase, with the most rain occurring in winter when there is the least evapotranspiration. Accumulation of water in the soil is therefore greater than in climates where the two are in phase, such as northern NSW. Differences in drainage risk due to differences in distribution are more noticeable between regions than within a region.

Crop vegetation management affects the conversion of evaporative demand into actual evapotranspiration. When the soil surface is bare, the conversion is inefficient except when the surface is wet, and therefore water tends to accumulate during fallow periods, especially if these occur at times of peak rainfall. Vegetation converts potential to actual evapotranspiration much more efficiently because it can extract water from the whole root zone and is not limited by the rate at which water can move to the surface.

Figure 1.4.3 Zero accumulation rate

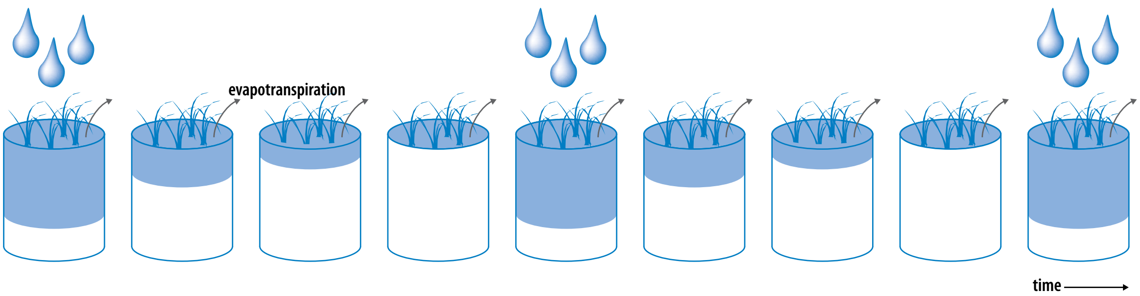
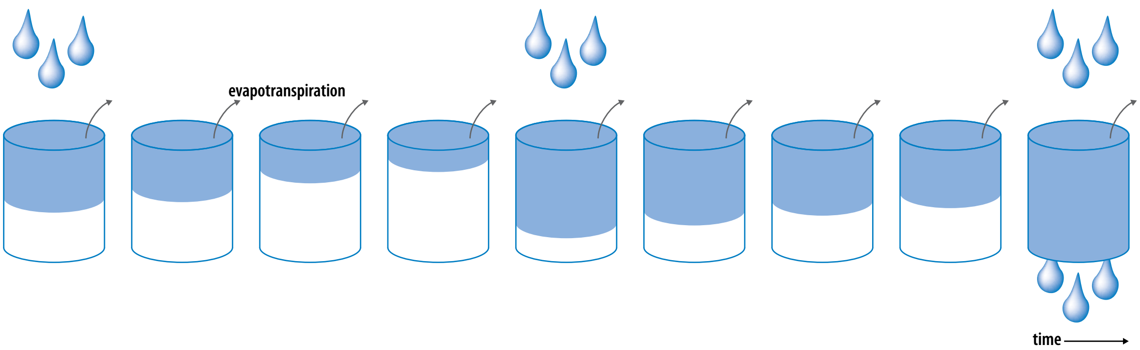


Figure 1.4.4 Positive accumulation rate



Irrigation management affects accumulation in several ways. First, it increases the total addition of water to the soil during the year – comparable to increasing mean annual rainfall – and this increases the risk of drainage. Second, within the growing season, over-irrigation causes drainage, because additions through irrigation are larger than losses. Correct scheduling ensures the amount of water added by each irrigation equals losses by evapotranspiration over the period between irrigations.

In summary, water tends to accumulate in three main situations:

- during winter when evaporative demand is low and, in some regions, when rainfall is greatest;
- during fallow periods when there is no extraction by plants and evaporation from the surface is limited once it has dried;
- when more irrigation water is applied than plants can extract.

Soil water deficit and bypass drainage: Bypass drainage can occur following furrow irrigation of cotton on Vertosols. Furrow irrigation appears to fully fill the available storage capacity of the upper 0.5 m of soil, but bypass drainage can occur even though the soil below this has empty storage. However, there is evidence (Ringrose-Voase and Nadelko, 2011) that the amount of bypass drainage decreases as the deficit of the subsoil (0.5-1.0 m depth) increases. This is because some water flowing through macropores in the subsoil is absorbed into the soil matrix depending on its dryness. For this reason irrigations later in the cotton season generally produce less drainage than earlier irrigations since the more mature and more deeply rooted crop can create greater subsoil deficit between irrigations.

Control of drainage

Of the many factors affecting drainage, only a limited number can be influenced by land management, and these can be grouped under four activities:

- improving subsoil structure
- using deep-rooted species
- maintaining an adequate soil water deficit
- managing irrigation in irrigated systems.

Improving subsoil structure

Removing barriers allows roots to exploit a greater depth of soil, especially useful in annual cropping (when the time available for root growth is limited). Methods include deep tillage to remove compaction, and controlled traffic and permanent beds to maintain good structure. These methods usually only lead to minor improvements in PAWC, because rooting depth is still limited by the species. Their chief benefit is in improving crop production.

Using deep-rooted species

Much greater increases in PAWC can be achieved by changing to deep-rooted species such as lucerne or trees. Deep-rooted species dry the soil to much greater depths, thereby creating much greater deficits (Figure 1.4.5) which provide greater buffering against drainage. This option usually involves changing to perennial vegetation, because annual species simply don't have the time to exploit a greater depth of soil.

Perennial species can either be used in permanent plantings or in sequence with crops.

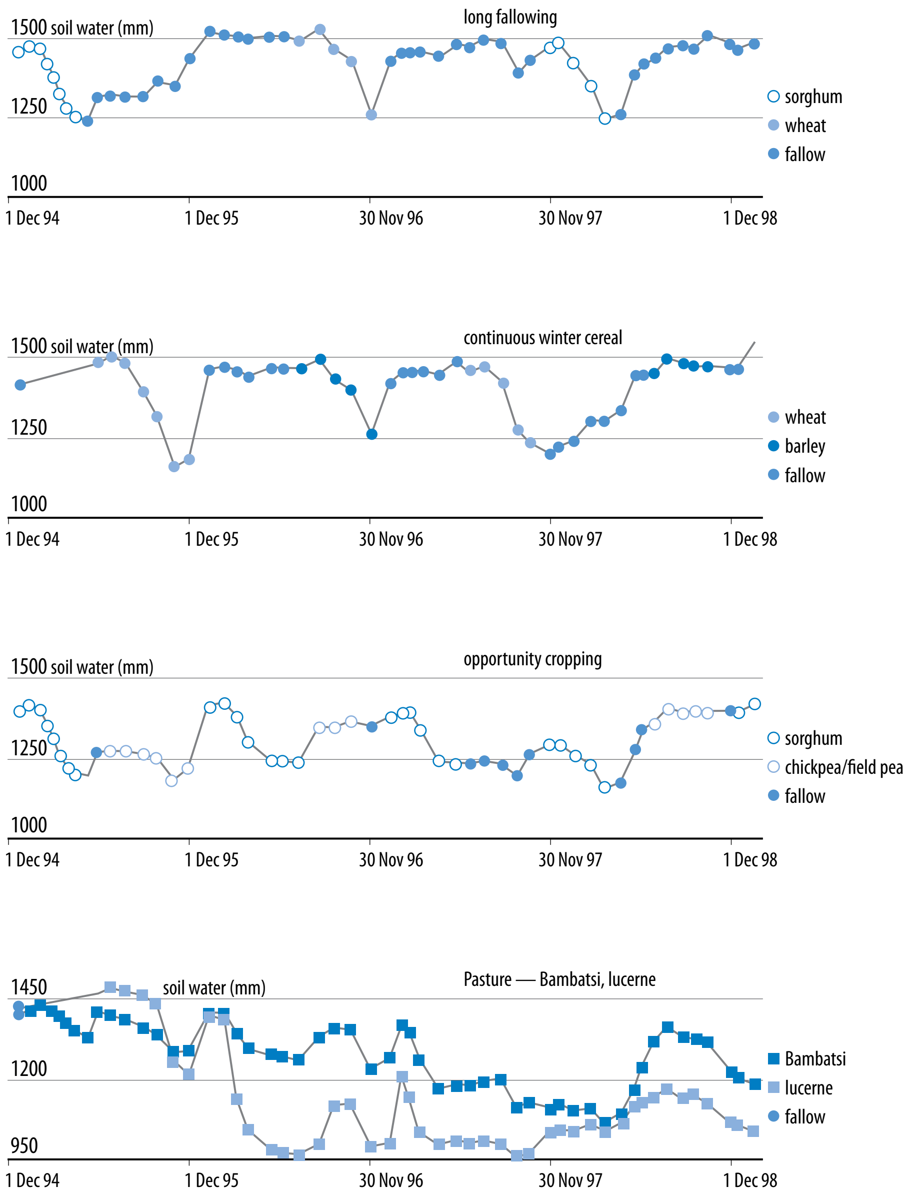
Permanent plantings reduce the proportion of the landscape prone to drainage, and if located strategically can use excess water from elsewhere in the landscape that could otherwise recharge groundwater. Whilst they can be economically productive, they are usually less so than cropping, but, in addition to reducing excess water in the landscape, they can provide benefits by forming windbreaks and by increasing biodiversity.

When perennials are used as part of a cropping sequence, the aim is to produce an additional temporary buffer of dry soil below the rooting depth of the crop species. The most common perennial species used is lucerne. The lucerne phase, which lasts for several years, dries the soil to a depth of two or more metres. During the subsequent cropping phase, drainage below the root zone of the crop is stored in the dry zone created by the lucerne. This temporary store gradually fills up until it is emptied again by the next lucerne phase.

The success of this system depends on changing phases at the correct time (Ridley et al. 2001). If cropping is continued for too many seasons, the temporary storage fills and drainage occurs. Conversely, if cropping phases are too short, profitability will suffer.

Improving subsoil structure and using deep-rooted species effectively increases the rooting depth and thus the PAWC and maximum possible soil water deficit. In soils with low water-holding capacity per unit depth – that is, those with narrow 'storage tanks' – increasing rooting depth may be the only way of having a large enough deficit to prevent drainage.

Figure 1.4.5. Total profile water (0.1–3.1 m depth) under various cropping or pasture systems measured by neutron moisture meter at a site in the Liverpool Plains



The soil is a Black Vertosol, and the mean annual rainfall is 684 mm/yr.

Source: Ringrose-Voase et al. 2003

Maintaining an adequate soil water deficit

Maintenance of an adequate soil water deficit provides a buffer against drainage. During periods of net accumulation of water, the deficit decreases until it is too small to accommodate the next rain or irrigation event.

The main ways to maintain an adequate soil water deficit are as follows:

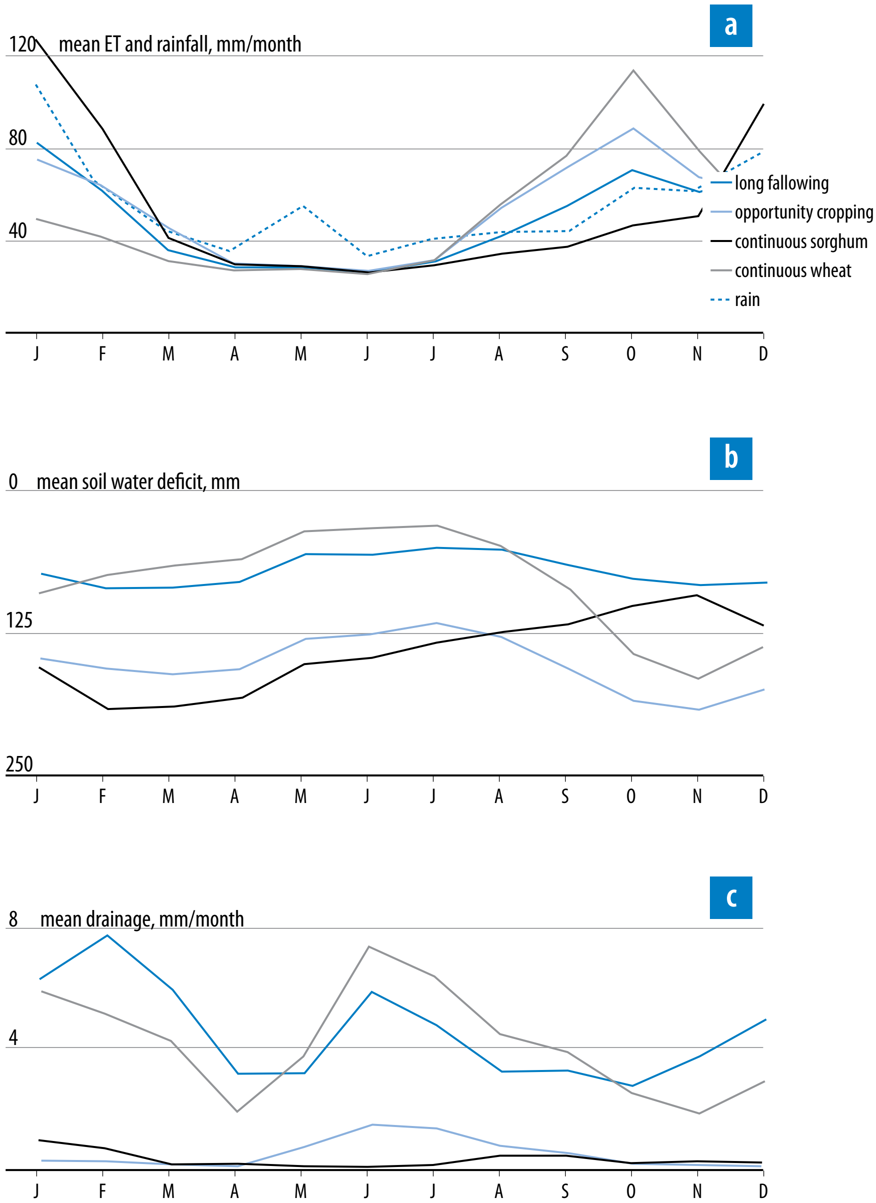
Decreasing the length of fallows between crops: When soil is left fallow it accumulates water (as long as weed growth is controlled). This provides extra water to the subsequent crop to supplement in-season rainfall, especially in soils with high water-holding capacity, such as vertosols. The fallow also increases the risk of drainage, because the deficit reduces as the fallow progresses. A compromise is clearly necessary that reduces the dependence of crops on in-season rainfall and minimises the risk of drainage.

For example, in the northern grains regions of New South Wales, a popular cropping system on vertosols is made up of one wheat and one sorghum crop every three years, separated by long fallows of about 12 months. The system has been popular because it provides reasonable yields even in seasons with lower than average rainfall. However, monitoring soil water under such a system has shown that this length of time is rarely required to refill the soil profile between crops, and that the deficit is dangerously small during much of the fallow period (Figure 1.4.5).

Long fallowing can be successfully replaced by response or opportunity cropping in which a decision is made during each spring and autumn sowing window on whether to sow a crop based on the amount of stored water. Wheat is sown in the autumn window only if there is sufficient depth of wet soil measured with a push probe, and similarly for sorghum in the spring window. Common rules for opportunity cropping in northern NSW are 70 cm of wet soil for wheat and 90 cm for sorghum. In this system, the fallow period is tailored to the weather conditions so that water is only allowed to accumulate up to a fixed amount.

For the climate and soil involved in Figure 1.4.6[b], the deficit under long fallowing declines to a minimum of about 75 mm in July, while the minimum under opportunity cropping is 135 mm, providing 60 mm of extra buffering against rainfall events. In this example, average yield per crop under opportunity cropping (3.9 t/ha/crop) is less than under long fallowing (5.0 t/ha/crop). However, average production per year is greater (4.5 t/ha/yr versus 3.1 t/ha/yr, respectively) because more crops are grown – 1.15 crops per year instead of 0.63. Average long-term gross margins are also greater ($340/ha/yr versus $240/ha/yr, respectively).

Figure 1.4.6. Predicted (a) mean monthly rainfall and evapotranspiration, (b) soil water deficit, and (c) drainage under various cropping systems



Same site as Figure 1.4.5, over 40 years (1958–98)

Note: Figure B present soils water deficit. Smaller values indicate a wetter profile, with zero indicating the PAWC is full. The vertical axis has been inverted so that plotted lines trend downwards as the soil dries.

Generating the maximum possible deficit before a prolonged period of accumulation: Sometimes periods of prolonged accumulation cannot be avoided because of the climate. In winter periods, evaporative demand is small, so any rain accumulates in the soil. However, the deficit before such periods can be maximised by better matching the peak water demand of the crop to the climate. In northern NSW rainfall is greatest in summer (Figure 1.4.6a), and the summer is long enough to allow summer cropping. In this region, peak water use by wheat is in spring before the summer peak in rainfall (Figure 1.4.6a).

Thus under continuous wheat the deficit is maximum (average 185 mm) in November (Figure 1.4.6b). This deficit is diminished by rain during both the subsequent summer and winter and reaches a minimum of about 60 mm in winter. This is often insufficient to buffer against drainage (Figure 1.4.6c). In contrast, peak water use by sorghum is in summer, coinciding with peak rainfall. Sorghum not only uses summer rain shortly after it falls – preventing its accumulation in the soil – but uses stored water as well. By March the deficit under continuous sorghum exceeds 200 mm. This is usually sufficiently large to store rain during the subsequent winter. In this example, both systems have the same cropping frequency, but quite different drainage outcomes.

Using permanent vegetation: The use of deep-rooted perennials to increase PAWC has already been discussed. An additional advantage of perennials and other permanent cover – such as permanent pasture – is that they have no fallow periods. Hence, the vegetation maximises the translation of evaporative demand at the surface into water removal from the soil (Figure 1.4.5).

Irrigation management

Irrigation increases the risk of drainage simply because it increases the input of water into the system, in the same way that drainage risk increases with mean annual rainfall (see above). However, unlike the climate, irrigation can be managed to ensure that all water added during the growing season is used to meet the dual aims of crop production and drainage minimisation.

- As the crop uses water, it increases the soil water deficit. Correct irrigation scheduling to meet the plant water requirements ensures that the amount of water added is equal to the soil water deficit.

  Over-irrigation occurs when the amount of water added is greater than the soil water deficit, and it directly causes drainage. It can be avoided by accurate irrigation scheduling and effective soil water monitoring. In addition, wetting front detectors can be buried in the soil at particular depths and used to show when infiltrating water has wet the soil to those depths (Stirzaker 2003). These devices have a role in teaching irrigators how much water is required to fill the root zone in different conditions. By placing them at different depths in the soil profile, irrigators can learn when over-irrigation is occurring.
- Enough time should be left at the end of an irrigated crop for the crop to dry the profile before harvest. This ensures the soil deficit is maximised before the fallow period, which is especially important when the fallow is during winter. Winter rainfall can cause drainage because low evaporative demand means water accumulates in the soil. This occurs even in regions where summer rainfall dominates, such as northern NSW.

Unfortunately, several factors make it difficult not to have drainage under irrigated paddocks.

- Standard irrigation practice requires a leaching fraction – a proportion of the irrigation water that is drained from the root zone – to prevent salts in irrigation water from building up in the root zone. The leaching fraction required increases as the quality of irrigation water declines. The leaching fraction directly adds to the total deep drainage. More information is included in WATERpak chapter 1.5.
- In some irrigation systems, it is believed that the economic penalty of under-irrigation far outweighs the economic savings achieved by very accurate scheduling – that is, it is better to slightly over-irrigate since the extra cost of water is much less than the value of lost production if the crop is water stressed. This strategy increases the amount of drainage.
- The unpredictability of rainfall during the growing season makes it difficult, if not impossible, to prevent drainage when rain falls on recently irrigated soil.

- In situations where bypass drainage can occur, for example furrow irrigation of cotton on Ve rtosols, it is particularly difficult to control drainage. Drainage tends to be greater when the subsoil is wetter. This can happen after a wet fallow period that wets the subsoil below 0.5 m. If early irrigation is required before the cotton crop is large enough to generate a deficit, large quantities of drainage can be produced. Whilst such irrigations cannot be avoided without damaging crop growth, they should be used as judiciously as possible.

Summary

While there are many factors affecting deep drainage, only some can be controlled by the farmer. Their relative magnitudes also vary. In a particular location, the degree of manipulation required to minimise drainage depends on those factors out of the farmer's control – soil and climate. Where soil and climate factors combine to give a high risk of drainage, greater manipulation of management factors is necessary.

The dryland management factors discussed above can be *approximately* ranked in order of increasing ability to control drainage. Note that improvements to irrigated systems, such as better soil water monitoring to improve irrigation scheduling, could potentially have a large effect on deep drainage because drainage tends to be larger under irrigated systems than under dryland ones. However, the magnitude of drainage reductions achievable relative to the list below is unclear and requires further research.

Level 1. Improving soil management – for example, by removing compacted layers – has a moderate effect on increasing the depth of the rooting zone.

Level 2. Increasing crop frequency shortens the length of fallows during which water accumulation occurs – for example, switching from long fallowing to short fallow wheat.

Level 3. In regions with summer-dominant rainfall, changing to summer crops whose maximum demand for water matches peak rainfall prevents summer rainfall accumulating by using the water shortly after it falls.

Level 4. Converting to cropping systems that are responsive to climate – for example, opportunity cropping – ensures that water accumulation is tailored to the needs of crops and does not lead to prolonged periods of low deficit.

Level 5. Changing to perennial pasture removes fallow periods altogether and ensures maximum translation of potential evapotranspiration into actual evapotranspiration.

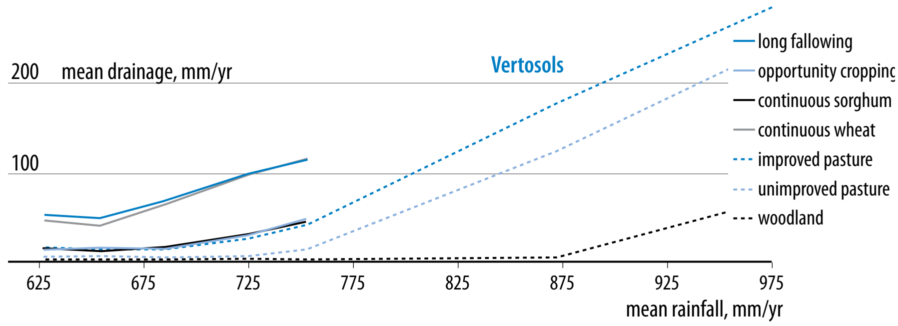
Level 6. Changing to deep-rooted perennial species – for example, trees or lucerne – removes fallow periods, as above, but also increases the depth of the root zone, thereby increasing the maximum possible deficit.

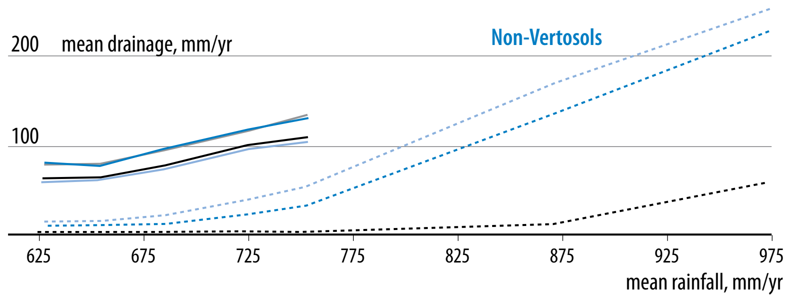
The degree of intervention required for a particular climate–soil combination is difficult to determine. Computer simulation of the land use system using long-term historical weather data is one way of comparing the potential leakiness of different systems.

For example, in Figure 1.4.7, computer simulation has been used to predict the drainage under a range of land uses on vertosols in the Liverpool Plains. At locations where mean annual rainfall is less than 700 mm/yr, the large PAWC of these soils means only quite mild intervention is required to reduce drainage to near natural levels (say level 3 and above in the list). There are a wide range of land use options available that are well buffered against drainage, including some profitable cropping options.

In areas where rainfall is greater than about 700 mm/yr, even the less leaky cropping options are no longer able to completely buffer against drainage and well-managed pasture or woodland (levels 5 and 6) are the only simulated options able to prevent drainage. These options provide buffering with mean annual rainfalls up to about 800 and 900 mm/yr respectively.

Figure 1.4.7 Predicted average annual drainage under different land uses at different locations in the southern Liverpool Plains of NSW





From a computer simulation using climatic data over 40 years, and characteristics of Liverpool Plains soils.

Figure 1.4.7 also shows the predicted drainage under the same land uses but on non-vertosols found in the Liverpool Plains. Because these soils have far lower PAWC than the vertosols, more drastic intervention is required to lower the risk of drainage. On these soils, none of the cropping systems perform well in terms of drainage and even well-managed pasture only provides a degree of buffering up to 700 mm/yr rainfall. In the areas with greater rainfall than this, the only option giving low drainage is woodland.

Whilst the generic principles outlined above can be used to reduce the risk of drainage, strategies for particular regions are the topic of much current research. Without data on local soil and climate and computer simulation of long-term performance, specific recommendations cannot be made reliably.

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1.5 Deep drainage under irrigated cotton in Australia: a review

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Key points

- Deep drainage varies considerably depending on soil properties and irrigation management, and is not necessarily 'very small' - 50-100 mm/yr is typical, though 0 to 900 mm/yr has been observed
- Soils used for irrigated cotton have much more diverse properties and management requirements than the simple description 'clay soil' suggests.
- Some drainage, or leaching fraction, is needed to avoid salt build up in the soil profile, but only where more saline water is used. This may be particularly relevant for CPLM and drip systems where the leaching fraction may not be provided by rainfall.
- The consequences of deep drainage are distinctly different where underlying groundwater can be used for pumping (fresh water, high flow rate) and where it cannot (saline water or low flow rate).
- Near saturated conditions can be found 2 to 6 metres under irrigated fields, conditions which do not exist under native vegetation.

Deep drainage describes movement of water below the root zone of crops. It is of concern, as it leads to:

- farming systems that are less water-efficient
- leaching of chemicals (for example, nitrogen), which may be a loss to the farming system and contribute to poorer off-site water quality, and
- raising of water levels in shallow groundwater systems.

It is now well accepted that deep drainage is a component of the water balance which needs to be managed. However this has not always been the case, as even in the early 2000's it was news that deep drainage might occur in the predominantly heavy clay soils used for irrigation in the northern Murray-Darling Basin and central Queensland regions. It had previously been assumed that deep drainage was likely to be 'very small' because heavy clay soils had low saturated hydraulic conductivity (k_{sat}) and because water input patterns (rain and irrigation) were more closely matched with crop water use and climatic demand than in southern Australia.

Early research (e.g. Shaw and Yule, 1978) had noted significant drainage and substantial leaching of chloride on a range of soils under irrigation in the Emerald area. Actual measurements of deep drainage on irrigated cotton soils began in the late 1990's and the results, indicating that drainage might be larger than first thought, prompted a concerted research effort that has continued for the best part of a decade. This chapter serves to summarise these various research efforts and provide guidance on the nature and management of deep drainage within irrigated cotton farming systems.

Shallow groundwater systems under the alluvial plains, at least in some places, are known to have a reasonable depth to the watertable (Free et al. 2001, Ian Heiner, NRM&E pers. comm.). There is a threat, but also an opportunity – time to do something to avoid potential problems, to investigate their extent, and to learn how to manage them.

Recent deep drainage studies

Lysimeter Studies

Northern MDB (McGarry and Gunawardena)

Starting in 2002, 27 non-weighing drainage barrel lysimeters (non-weighing) were installed across nine irrigated cropping sites in the Northern Darling Basin of QLD and NSW to monitor deep drainage. A full description of the lysimeters and results is available online. Deep drainage was measured under a range of cotton and grain crops as well as fallow conditions and ranged from 0 mm per season to 235 mm per season. In the case of the maximum value, this represented 27 per cent of the applied water (rainfall + irrigation).

However, there were many examples at all sites where little or no deep drainage was recorded and only about 20 per cent of seasons had measured deep drainage greater than 100 mm (1 ML/ha). Furthermore, individual sites exhibited considerable seasonal variability in drainage (Table 1.5.1). For example, the 'Macalister' site recorded 175 mm of deep drainage at the head of the field in the 2002–03 season, then only 5 mm at the same location in the 2003–04 season. In some seasons very low values of deep drainage were recorded across many sites, potentially due to a combination of limited water supply and above average evapotranspiration.

Table 1.5.1 Deep drainage (DD) calculated from the measured leachate volumes (mm) at the head, mid and tail locations from the nine DD monitoring sites. Also presented is the DD data, expressed as the leaching fraction; LF= (DD) / (rain + irrigation) * 100

Site	Crop	In crop rain (mm)	Irrigation (mm)	Season	Head		Mid		Tail	
					Vol.	LF	Vol.	LF	Vol.	LF
Boggabilla										
(a) furrow	Cotton	331	628	05/06	105a	11	87	9	92	10
	Fallow	261	-	06/07	0	-	0	-	0	-
	Cotton	350	450	07/08	19	2	40	5	1c	0
	Fallow	328	-	08/09	0	-	0	-	0	-
	Cotton	320		09/10	14		2			
	Fallow			10/11	0	-	0	-	0	-
(b) lateral move	Cotton	331	270	05/06	31	5	0	-	0	-
	Cotton	261	196	06/07	0	-	0	-	0	-
	Cotton	350	131	07/08	0	-	0	-	0	-
	Chick pea	112	30	2008	0	-	0	-	0	-
	Sorghum	328	60	08/09	0	-	0	-	0	-
	Cotton	320		09/10	0	-	0	-	0	-
	Cotton			10/11	0	-	0	-	0	-
Dalby										
	Cotton	302	465	04/05	39	5	95	12	34	4
	Soybean	449	400	05/06	0	-	0	-	0	-
	Sorghum**	274	100	06/07	0	-	17	5	0	-
	Cotton***	502	100	07/08	0	-	0	-	0	-
	Fallow	351		08/09	0	-	0	-	0	-
	Fallow	466		09/10	0	-	0	-	0	-
	Cotton			10/11	4		0	-	0	-
Dirranbandi										
	Cotton	260	926	03/04	11	1	21	2	176b	15
	Cotton	251	600	05/06	0	-	1c	0	6	1
	Fallow	112	-	06/07	0	-	0	-	0	-

Goondiwindi										
	Maize	247	*	02/03	187b	*	196b	*	24	*
	Sorghum	400	462	03/04	235a,b	27	101	12	21	2
	Cotton	317	563	04/05	104a	12	23	3	19	2
	Sunflower	188	420	05/06	0	-	1c	<1	11	2
	Fallow	210	-	06/07	0	-	0	-	0	-
	Fallow	383	-	07/08	0	-	0	-	0	-
	Mixed seed	211	*	2008	0	-	0	-	0	-
	Fallow	435	-	08/09	0	-	0	-	0	-
	Sorghum	324		09/10	2	-	0	-	0	-
	Cotton			10/11	0	-	0	-	0	-
Macalister										
	Maize	297	*	02/03	175a,b	*	nf*	-	51	*
	Sorghum	364	720	03/04	5c	<1	nf*	-	33	3
	Cotton	270	335	04/05	41	7	101	17	0	-
	Cotton	107	540	05/06	12a	2	10	2	0	-
	Cotton	78	420	06/07	31	6	26	5	0	-
	Fallow	542	-	07/08	31	6	26	5	0	-
	Barley	278	*	2008	41a	*	6c	-	0	-
	Fallow	298	-	08/09	13a	4	0	-	0	-
	Cotton	382		09/10	16		52		0	-
	Field pea/Cotton			10/11	7		3		0	-
Pampas										
	Cotton	506	963	04/05	71	5	106	7	62	4
	Sorghum	432	-	05/06	0	-	0	-	0	-
	Fallow	209	-	06/07	0	-	0	-	0	-
	Sorghum	341	-	07/08	0	-	0	-	0	-
	Sorghum	390	-	08/09	0	-	0	-	0	-
	Fallow	453		09/10	0	-	79	-	7	-
	Cotton			10/11	12		1		3	
St George										
(N)	Wheat	75	*	2004	24	*	55	*	1.6c	*
	Cotton	236	693	05/06	27a	3	22	2	0	0
(S)	Cotton	144	*	02/03	14	*	68	*	37	*
	Cotton	374	800	03/04	104a	9	91	8	18	2
	Cotton	375	734	04/05	40	4	92	8	50	7
	Field pea	323	493	05/06	5c	1	37	5	33	7
	Cotton	125	700	06/07	0	-	33		0	-
	Fallow	532	-	07/08	14	3	1c	0	13	2
	Wheat	133	*	2008	0	-	0	-	0	-
	Fallow	180	-	08/09	0	-	0	-	0	-
	Cotton	548		09/10	18		104		0	-
	Field pea/cotton			10/11	0	-	8		0	-

nf = non-operational lysimeter; replaced before the 2004-05 season

a,b & c are first three drainage characteristics described in the text (Gunawardena et al, 2011)

** Irrigation waters applied, not known.*

*** Sorghum irrigated to establish, only (note the 17 mm of DD resulted from the one irrigation)*

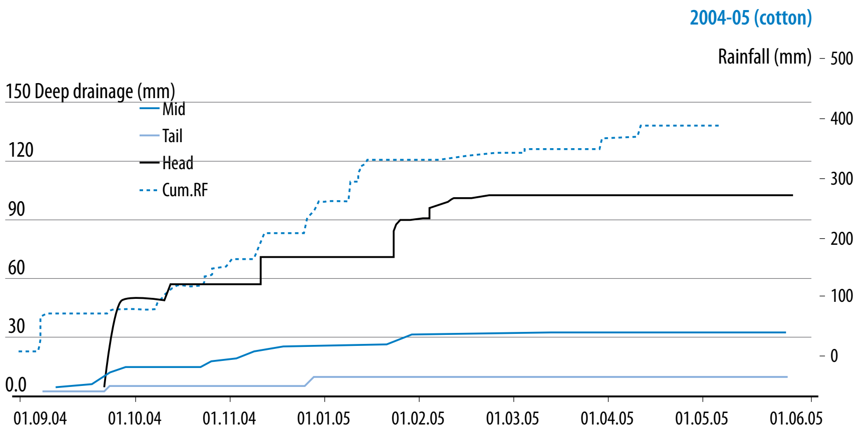
**** Cotton irrigated only once on 9 Jan 08.*

Note: lysimeters were installed at different sites in different years.

On furrow irrigated fields, deep drainage was measured at three points from the top of the field to the bottom, with drainage typically reducing from head to tail ditch. This is consistent with the theoretical pattern of water infiltration in furrow irrigated fields where non-uniformity, if it occurs, results from greater water infiltration at the top of the field which reduces toward the bottom. Improved furrow irrigation management over the past decade has resulted in improved uniformity, although it is unclear whether this is evident in the deep drainage data.

Deep drainage was also found to be most prevalent at the start of the irrigation season, so any reduction in water applied in the pre or first irrigations can dramatically reduce deep drainage. For example, Figure 1.5.1 shows the deep drainage for the 2004–05 season at Goondiwindi. Large 'step' increases can be seen at the time of the first and second irrigations, after which there was almost no deep drainage at the head, mid or tail locations. In this case, the first three irrigations accounted for 80 per cent of the total deep drainage for the season.

Figure 1.5.1 - Cumulative deep drainage and rainfall from the Goondiwindi site during the 2004–05 season. Vertical arrows indicate irrigation events.



One site was under lateral move irrigation, which had an up to 59 per cent reduction in water applied with equivalent yield, although the almost total lack of deep drainage could be leading to salt accumulation in the rootzone. Longer monitoring is required to derive conclusions at this site.

Deep drainage leachates at all sites have been found to be very salty relative to the quality of the irrigation waters applied, showing the great potential of salts being moved to rivers and groundwaters. This showed that irrigation management needs to balance leaching requirements and deep drainage to minimise the potential for rootzone salinity as well as off-site drainage impacts.

Based on analysis of soil and leachate quality, the leaching requirement (LR) to maintain maximum yields was calculated. The leaching requirement is the proportion of applied water (irrigation and rainfall) that needs to drain past the root zone to avoid soil salt accumulation in the soil. The allowable soil salinity limit depends on the sensitivity of the crop type with calculations here being for cotton.

The leaching requirement for all sites except one was less than 3.5 per cent, with the remaining site (leaching requirement of 12.1 per cent) utilising the poorest quality irrigation water (Table 1.5.2). For most sites, although there were a number of seasons where deep drainage was zero, when drainage did occur it was often in excess of the leaching requirement, indicating that excess drainage occurred on these occasions. At the 'Macalister' site, the leaching fraction was only larger than the LR on one occasion, indicating a potential build-up of salts in the rootzone at this location. This is supported by the analysis of leachate EC where the 'Macalister' site was found to have the highest leachate EC of all sites.

Table 1.5.2 – Leaching requirement for each site to maintain potential yield for cotton (saturation extract EC = 7.7 dS/m) for the given irrigation water quality (EC_{iw}).

Site location	EC_{iw} (dS/m)	LR (%) for Potential yield
Boggabilla	0.70	1.9
Dalby	1.31	3.5
Dirranbandi	0.18	0.5
Goondiwindi	0.50	1.3
Macalister	4.15	12.1
Pampas	0.31	0.8
St George (north)	0.31	0.8
St George (south)	0.14	0.4

Narrabri (Ringrose-Voase)

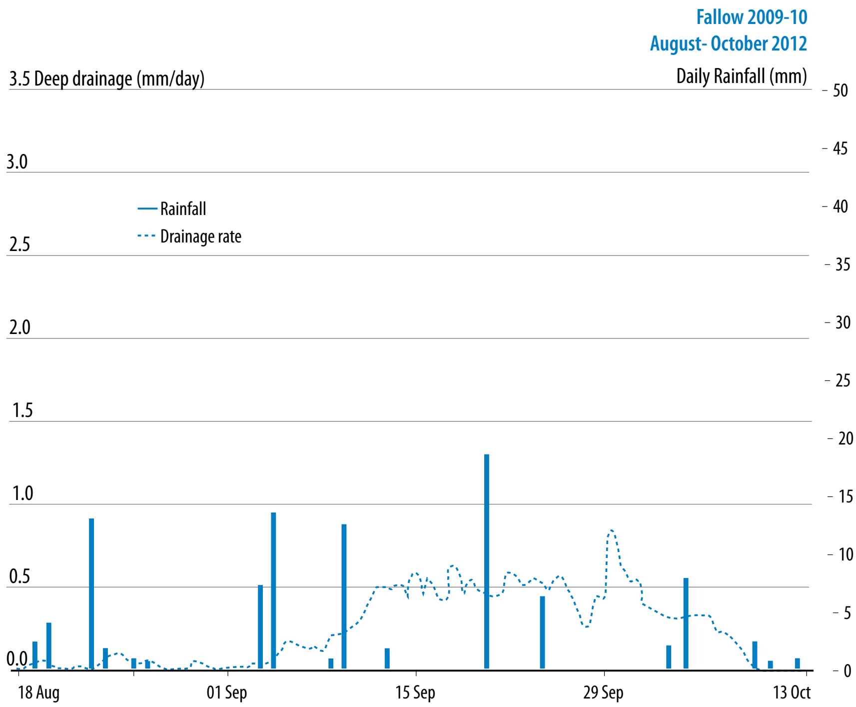
Since 2006, an equilibrium tension lysimeter has been directly measuring deep drainage at the Australian Cotton Research Institute (ACRI) at Narrabri. Six lysimeter trays collecting drainage over an area of 1.6 square metres were installed by tunnelling horizontally at 2.1 m depth from an access shaft, leaving the overlying soil undisturbed (Figure 1.5.2). This type of lysimeter is able to accurately measure drainage by applying a vacuum to the collection trays that is constantly adjusted so that it is equal to the suction of the soil at tray depth. A full description of the lysimeter facility and the results is available online. Deep drainage was measured under cotton, wheat and fallow conditions and ranged from 0 to 74 mm per season.

Figure 1.5.2. The ACRI lysimeter facility. A: The access shaft showing showing the window through which the access trays were installed (top) and the six tanks which collect the drainage. B: One of six collection trays being installed into the horizontal tunnel.

It was also found that deep drainage in cracking clay soils occurs in two ways; bypass drainage and matrix drainage. Matrix drainage occurs when a wetting front moves downwards through the soil, generally over several weeks or months, filling the water holding capacity of the soil until water leaves the root zone as drainage. Bypass drainage occurs when there is 'free' water on the surface such as during furrow irrigation, and occurs very rapidly, within hours or days, with water flowing down cracks and macropores, 'bypassing' the bulk of the soil.

Matrix drainage is well illustrated by a drainage event in September 2010 after about nine months of fallow following a wheat crop. The crop had created a soil water deficit of 200mm. After harvest, 640 mm of rain fell over nine months, wetting up successively deeper layers until the wetting front reached two metres. During the next 35 days the event generated 14 millimetres of drainage. The drainage rate increased slowly over the first 10 days to 0.5 millimetres per day, remaining at this rate for 20 days before slowly decreasing to zero (Figure 1.5.3).

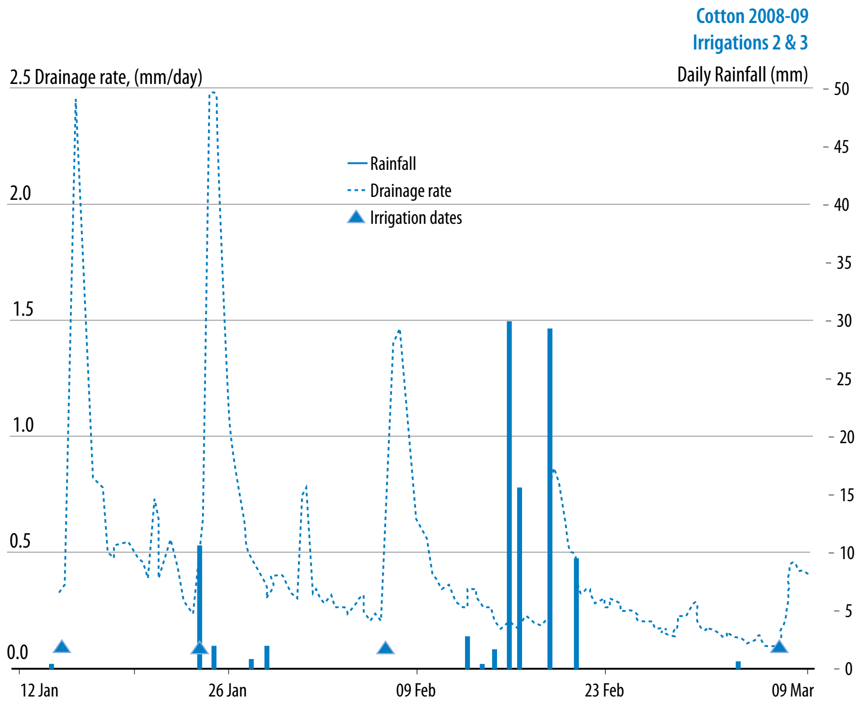
Figure 1.5.3 - Fluctuations in the drainage rate during part of the 2009–10 fallow showing a period of matrix drainage.



Matrix drainage is the 'normal' drainage mechanism in most soils under dryland or irrigated land uses. Its basic cause is that the infiltration of water over an extended period exceeds evapotranspiration, until the soil water holding capacity is exceeded. In contrast to matrix drainage, bypass drainage occurs very rapidly and often in greater volumes. It is of importance in only a few situations – furrow irrigation of cracking clay soils being one of them.

During the 2008–09 cotton season, the drainage rate at two-metres depth typically started increasing just six hours after the irrigation front passed overhead and peaked 25 hours after irrigation before declining rapidly (Figure 1.5.4). The peak rate was greatest after the first irrigation at 3.2 mm per day and was less after later irrigations. Whilst irrigation fully wet the top 0.5 metres of soil, it often did not fully wet the soil below 0.5 metres depth despite causing drainage. The speed with which drainage occurred after irrigation and the fact that the sub-soil was not fully wet both suggest that water moves rapidly down macropores 'bypassing' much of the soil matrix

Figure 1.5.4 - Fluctuations in the drainage rate during the 2008–09 cotton season showing a peaks of bypass drainage following each irrigation event and periods of heavy rain.



The quantity of drainage generated by individual irrigation events varied considerably (Table 1.5.3). There is some evidence that the amount of bypass drainage is greater when the upper 0.5 metres is drier – presumably due to larger cracks. On the other hand, drier soil between 0.5 and 1.0 m reduces the quantity of bypass drainage, possibly because the drier soil 'sucks' more water into the matrix as it flows down the macropores. This is why irrigations later in the season generally produce less drainage since the crop has extracted more water from the subsoil. Conversely irrigations early in the season, before the crop is extracting water from the sub-soil, can generate large quantities of drainage as, for example, during 2006–07 season when early irrigation was required due to a lack of early season rain.

Table 1.5.3 – Seasonal drainage and leachate electrical conductivity at the ACRI lysimeter. Amounts shown are from the date of the event until the date of the next event shown on the next row. "↓" indicates there was too little drainage for collection and analysis, so drainage was accumulated over several events.

Event	2006-07			2008-09			2010-11		
	Date	Drainage (mm)	EC (dS/m)	Date	Drainage (mm)	EC (dS/m)	Date	Drainage (mm)	EC (dS/m)
Sowing	19–Oct–06	0		09–Oct–08	5.5	3.4	04–Nov–10	0.4	↓
Irrigation 1	24–Oct–06	8.8	3.1	22–Dec–08	13.3	3.8	20–Jan–11	0.1	↓
Irrigation 2	22–Nov–06	22	2.2	12–Jan–09	7.3	2.9	02–Feb–11	0.1	4.9
Irrigation 3	12–Dec–06	34.7	2.1	22–Jan–09	8.6	2.6	17–Feb–11	0.1	↓
Irrigation 4	03–Jan–07	3.6	2.1	05–Feb–09	9.3	3.6	01–Mar–11	0.1	↓
Irrigation 5	16–Jan–07	0.2	2.2	06–Mar–09	2.5	5.5	16–Mar–11	0.1	3.7
Irrigation 6	30–Jan–07	0.5	2.5	19–Mar–09	7.4	8.1			
Irrigation 7	14–Feb–07	2.1	2.6						
Irrigation 8	28–Feb–07	2.3	3.2						
End	18–May–07			23–Jun–09			24–Jun–11		
Season Total		74.2			53.9			0.7	

Some drainage is necessary in irrigated systems in order to leach salts that would otherwise build up near the bottom of the root zone. Electrical conductivity (EC) measurements of the drainage give an indication of how effectively it leaches salt (Table 1.5.3). Bypass drainage generally has relatively low EC – 2 to 3 dS/m, because the irrigation causing it does not pass through the matrix of the lower root zone where salt has accumulated.

Matrix drainage leaches salt much more efficiently, as shown by the increase in EC in the drainage at the end of most seasons. The greatest EC values, 13 dS/m, occurred in drainage towards the end of the 2009 wheat crop (winter crop data not shown in table).

Drainage can also remove nitrogen fertiliser from the soil root zone. For example, 9.5 kilograms per hectare were leached out during the 2008–09 season, mainly following the first four irrigations. Unfortunately, nitrogen (unlike salt) is most available in the top soil where it is efficiently mobilised by irrigation water, so that it can be leached by bypass drainage. This again shows the importance of avoiding early season drainage, when nitrogen is most available.

The interaction between root zone drainage and watertable recharge was also investigated. The watertable is about 16 metres below the surface under the lysimeter. Two piezometers (screened at 20 and 34 metres below ground surface) monitored the groundwater in the upper two aquifers. Recharge into the upper aquifer could be identified using the relative changes in the heads of the two aquifers. Preliminary results suggest that the peak in seasonal recharge into the upper aquifer may occur just 15 days after the peak in seasonal deep drainage at two metres.

Darling Downs (Moss)

Like the ACRI lysimeter, Moss et al. (2001) measured deep drainage directly, using suction lysimeters of considerable area (3 m x 1.5 m) compared with most other methods. These lysimeters collect drainage by applying suction to the soil 2 metres under the surface. They also have the advantage of collecting all drainage, whereas other methods (e.g. measured water balance) may miss some periods of drainage and often depend on imprecise soil moisture measurements.

Lysimeters were installed under nearby fields irrigated by furrow and sub-surface drip systems. Under furrow irrigation, annual deep drainage (over 3 yrs) was 150-180 mm, about 20% of the total rainfall plus irrigation (Table 1.5.4). Deep drainage under sub-surface drip irrigation was more variable (95 and 305 mm/yr) than under furrow and was quite high considering about half the irrigation water was applied. Drainage occurred under both systems within a day of irrigation. Rainfall events following soon after irrigation caused significant drainage. In 1998-99, a large amount of drainage occurred (809 mm) when rainfall/flood water was ponded over the sub-surface irrigation lysimeter for an extended period (a natural occurrence on floodplains).

The data illustrate that under saturated conditions there is significant drainage through this heavy clay soil (Moss et al. 2001). Soil moisture data indicated soil at 1.75 m depth (i.e. below the root zone) was continuously moist (at or above 'field capacity'). Significant quantities of nitrate N (a loss to production), chloride (which may contribute to salinity of groundwater) and traces of pesticides were measured in the drainage water.

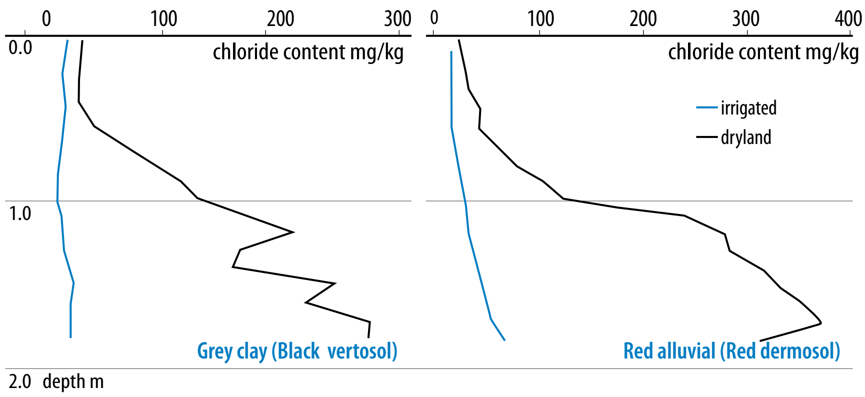
Table 1.5.4. Deep drainage (below 2m) measured using suction lysimeters near Macalister, 50 km NW of Dalby, for adjoining fields under furrow and sub-surface drip irrigation. Data are annual total (June-June). Soil is a Grey Vertosol (clay 75-80%, ESP 10-30 below 30cm). (Source: Moss et al. 2001).

Field	Year (mm)	Irrigation (I) (mm)	Rainfall (R) (mm)	Total (mm)	Drainage (mm)	Drainage (% of I+R)
Furrow irrigation	96-97	327	478	805	182	23%
	97-98	343	667	1010	162	16%
	98-Jan99	337	579	916	152	17%
Sub-surface irrigation	96-97	150	478	628	305	49%
	97-98	142	667	809	95	12%
Flood over lysimeter	98-99	0	739	Unknown	857	n.d.

Soil properties and solutes studies

Chloride (Cl) concentrations in the soil profile provide an insight into past drainage through a soil. This is because chloride, which occurs naturally in rain, soil and streamflow, is soluble and mobile in soils, and in the long term moves where the water moves. Under native vegetation, pasture and dryland cropping, chloride concentrations typically increase with soil depth (a 'chloride bulge') due to storage of historic chloride from rainfall (Figure 1.5.5). Irrigated fields in the Gwydir Valley (Figure 1.5.5) have lower Cl concentrations in the soil profile than adjacent dryland sites, indicating that chloride has been leached downwards, and drainage is greater than under dryland cropping.

Figure 1.5.5. Soil chloride profiles in irrigated and nearby dryland cropping fields, on two soils in the Gwydir Valley, NSW



Source: J. Montgomery

Willis and Black (1996) also found lower soil chloride for irrigated sites compared with non-irrigated sites in the Macquarie Valley for 4 soils (generally 'lighter textured' soils, although one was a grey vertosol). They used measured changes in soil chloride profiles and transient chloride mass balance to calculate long-term changes in deep drainage associated with flood irrigation. Their results (Table1.5.5) indicate a wide range in the increase in deep drainage under irrigation, with a larger increase for the lightest textured soils. Partly because of their greater drainage, the lightest textured soils received more irrigation water, thus further contributing to greater drainage.

Table 1.5.5 Increase in drainage below the root zone under irrigation compared with non-irrigated sites, calculated using soil sampling and transient chloride mass balance

Soil		Clay content (%)		Irrigation water applied	Increased deep drainage under irrigation	
Local name		A horizon	B horizon	(mm/yr)	(mm/yr)	LF* (%)
Mullah	Grey vertosol	51	53	491†	17	3
Mitchell poorly drained	Uniform silty loam	16	46	400	45	11
Wilga non calcic	Duplex	19	35	811	206	25
Macquarie	Duplex	39	38	860	131	15

* Leaching fraction – increased deep drainage as a proportion of irrigation water input. † 100 mm = 1 ML/ha.

Source: Willis and Black 1996

The increase in drainage was lower on higher clay soils (Mullah and Mitchell), due to their higher water-holding capacity, leading to less frequent irrigation, lower drainable porosity and (presumably) lower subsoil permeability. The low drainage for the grey vertosol (assuming the increased drainage is close to total drainage) is roughly equivalent to the drainage estimated for sodic grey vertosols in the Namoi Valley, discussed below (Table 1.5.6).

Thorburn et al. (1990) analysed soil chloride (Cl) profiles for 42 irrigated sites in Queensland (central Queensland and the Lockyer Valley) and determined deep drainage from transient Cl mass balance. Non-irrigated Cl profiles were assumed to represent the soil prior to irrigation.

- Soils were mainly black and grey vertosols and a range of other soils: for example, clay content ranged from 17% to 70%, and exchangeable sodium percentage (ESP) 1–40.
- Drainage was 0–100 mm/yr for about half the sites, 100–300 mm/yr for 18 sites and 500–1200 mm/yr for 3 sites. On one soil with a drainage rate of ~0 mm/yr, the chloride data indicated the presence of a high watertable preventing drainage and contributing chloride.
- Time to establish a new soil chloride equilibrium under irrigation mostly ranged from 3 to 40 years, depending on the drainage rate and irrigation water salinity, but was as short as 1 year with very high drainage and 50–100+ years for soils with low drainage rates. The new equilibrium under irrigation involved cases of both increased soil chloride (salinisation) and decreased soil chloride.

Zischke (NRM&E, pers. comm.) used measured soil properties (Moss et al. 2001) and the SaLF model (Shaw and Thorburn 1985) to estimate deep drainage for non-irrigated and irrigated soils in cotton regions (Table 1.5.6). SaLF is an equation that estimates steady state drainage (or leaching fraction) under irrigation from rainfall, irrigation applied and soil properties.

- Irrigated sites had a much higher drainage than dryland sites.
- Under irrigation, a wide range of drainage occurred, depending on soil properties. Generally, under irrigation, Macquarie soils (lighter textured, greater irrigation used) had high drainage potential; Darling Downs soils intermediate but still considerable drainage potential (200–300 mm/yr); and Namoi soils (sodic grey vertosols), low (but not insignificant) drainage.

Only a few soils in each region were considered. A range of soils and drainage potentials occur within each region, as illustrated by Thorburn et al. (1990) and Willis and Black (1996). The Namoi soils considered were grey vertosols, with very high subsoil sodium (ESP) and lower salt levels: both of these factors contribute to lower permeability.

Table 1.5.6 Deep drainage below the root zone estimated using paired site soil sampling (dryland non-irrigated and irrigated) and the SaLF model

Location	Number of soils	Under rainfall/ non-irrigated		Irrigated	
		Leaching (%)	Drainage (mm)	Leaching (%)	Drainage (mm)
Average	22	1.2	8	30	210
Darling Downs	7	0.3	2	24	266
Namoi (grey clays [A])	5	0.2	1	2	27
Macquarie	6	3	19	52	754[B]

[A] soils with very high subsoil ESP (sodium) and lower salt levels.

[B] lighter textured soils and higher irrigation, thus more drainage.

Source: R Zischke, NRM&E, based on Zischke and Gordon 2000, Moss et al. 2001

Where irrigation water contains high levels of salts (for example, bore water of marginal water quality), salinisation of soil profiles has occurred. See, for example, some soils in the Lockyer and Dee valleys (Thorburn et al. 1990) and the Condamine alluvial plains (Ian Gordon NRM&E, pers. comm.). Sodium content of irrigation water is also important, as accumulation of the salt sodium (sodicity) can occur, and this has adverse effects on soil properties and manageability. Increased salinity in streams, a major source of fresh irrigation water, is a threat to the irrigation industry.

Water Balance Studies

Water balance studies are those which aim to infer drainage by measuring or modelling all other inputs and outputs of water to the soil and thus estimating drainage as the only output that remains unaccounted for. Considerable time, effort and money has been invested in 'water balance' related research over the past two decades. Whilst soil water balance models can be used to answer critical questions affecting the industry, a lack of key soil physical data, particularly the soil water holding capacity, has traditionally limited the use of water balance models to determine the relationships between irrigation management and deep drainage.

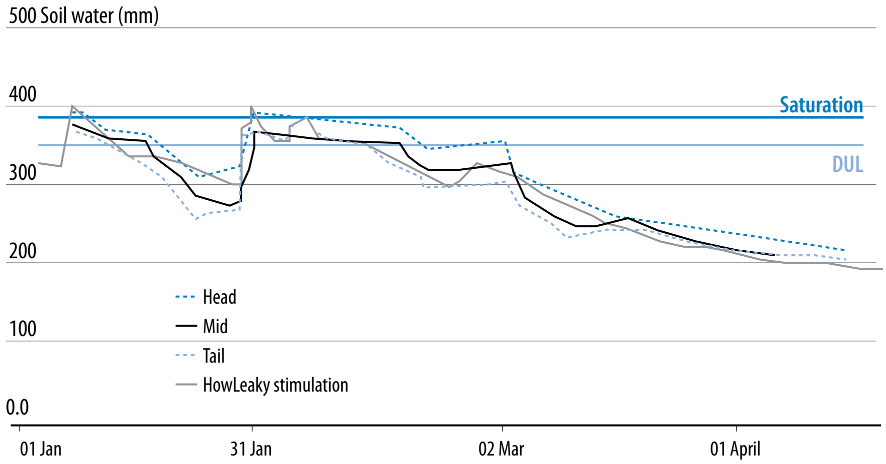
A recent project (Silburn and Foley) captured data from past and current studies of water balance and deep drainage under irrigation in northern NSW and south-west Qld in a form useful for modelling, and 'filled in' some of the gaps with additional paddock measurements at key sites.

Soil water balance models such as HowLeaky? are used to look at the relationships between management options such as irrigation frequency and amount, and components of the water balance that we wish to manage, such as deep drainage. To test this model, an EM38 device (Geonics Limited) was used to indirectly measure soil water, with the readings calibrated against soil water measured with a soil coring rig. EM38 readings at a number of heights above ground (called depth slicing) were also used to get specific detail on where the water was located within the root zone during the season.

The EM38 provided soil water estimates for various soil layers with better accuracy and less time taken than most other soil water monitoring methods (once paddock calibrated). Measurements were made before and after irrigations (two irrigations – each about one megalire per hectare) and then frequently during the course of the growing season. Variations in water application from head, mid and tail positions could be estimated with great precision, and the variability in row and inter-row wetting during irrigations could also be determined.

The paddock was very wet (draining) for much of January-April. The data was modelled with HowLeaky? Which was found to be capable of simulating, with reasonable accuracy, the changes to soil water during the growing season (see Figure 1.5.6).The model agreed to a large degree with the data, estimating that during two periods in the season, a significant amount of deep drainage (1000 mm) occurred.

Figure 1.5.6. Cumulative soil water to 0.65 m measured with the EM38 for head, mid and tail positions in the paddock – and simulated using the HowLeaky? model.



Measured water balance studies (Janelle Montgomery)

This study determined deep drainage below the root zone for an irrigation season (or part of a season) on three soils under furrow irrigation, using the 'measured water balance method'.

Measurements were made of soil moisture contents before and after each irrigation (ΔS), and irrigation (I), rainfall (P), run-off (R) and evapotranspiration (ET) amounts.

Deep drainage was calculated as

$$DD = (P+I) - (ET+R+\Delta S)$$

for the period between soil moisture sampling. Average drainage per irrigation (Table 1.5.7) was

- 40 mm for the grey vertosol (Gwydir)
- 8.8 mm on the red alluvial (Gwydir)
- 1.5 mm for the grey vertosol (Namoi).

Rainfall during one irrigation period contributed to greater drainage on the Gwydir grey vertosols, although 45% of rain plus irrigation ran off, but drainage was still 23–40 mm per irrigation during other irrigations. Total measured deep drainage for the irrigations monitored was 158 mm and 53 mm for Gwydir grey and red soils, and about 9 mm (assuming 1.5 mm × 6 irrigations) for the Namoi grey vertosol. Total drainage for the season may be greater than these amounts, if drainage continued between the measurement periods or if other irrigations or larger rainfall events occurred.

Table 1.5.7 Water balance components measured under furrow irrigated cotton, each for part or all of one irrigation season, where deep drainage = (I+P)−(R+ET+ΔS) for the period between soil moisture measurements before and after irrigation.

Date	Irrigation (I) (mm)	Rainfall (P) (mm)	Run-off (R) (mm)	ET (mm)	ΔS (mm)	Drainage (mm)
Grey vertosols, Gwydir (4 irrigations)						
19/12–24/12	96.8	0	12.5	24.0	26.1	34.2
6/1–8/1	115.1	0	7.8	13.1	54.2	40.0
21/1–26/1	89.6	157.8	110.2	39.2	36.9	61.2
1/3–4/3	86.9	3.6	8.0	22.3	37.8	22.5
Total	397	161	139			158
% of I+P			24			28
mm/irr			34.6			39.5
Red alluvial, Gwydir (6 irrigations, totals)						
Total	372	19	34			53
% of I+P			11%			14%
mm/irr			5.6			8.8
Grey vertosols, Namoi (2 irrigations, totals)						
Total	176	0	8.8			3
% of I+P			5%			1.7%
mm/irr			4.4			1.5

Measured and modelled water balance, Emerald

Connolly et al. (1998, 1999) used measured water balance (rain, irrigation, run-off and soil moisture) and agronomy from furrow-irrigated cotton fields in the Emerald Irrigation Area (EIA) (Carroll et al. 1995, Simpson et al. 1998) to calibrate a daily water balance model (GLEAMS). While the intention was to model run-off rather than drainage, the model accounts for all the water balance components and calibration generally forces a reasonable representation of each component.

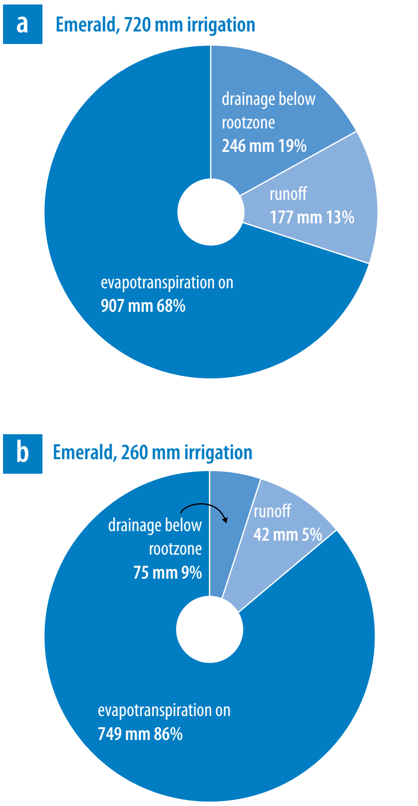
The results (Figure 1.5.7a) indicate considerable deep drainage is likely when irrigation of 7.2 ML/ha/yr is applied (720 mm/yr), that is, about the average used for cotton crops (Hearn 1998). Drainage (246 mm) and leaching fraction (19%) are similar to those from the furrow-irrigated lysimeter study (LF=~20%) (Table 1.5.4) and SaLF model results for Darling Downs soils (Table 1.5.6). Average annual run-off is similar to the average measured over 12 years in the EIA (174 mm) (Silburn et al. 1997, 1998). Total annual ET (907 mm) is above that estimated for a typical growing season (700–750 mm) (S Milroy, Cotton CRC, pers. comm.), as it also included soil evaporation during the non-crop season.

What the model is telling us is that if you put 720 mm of irrigation and 600 mm of rain per year on a cotton field, it has to go somewhere – unless ET is considerable larger than estimated here, about 250 mm must have been lost as deep drainage.

When considerably less irrigation is used (average 260 mm/yr, 2.6 ML/ha/yr), mimicking a system with 'perfect' irrigation, that is, only just refilling the soil water deficit to field capacity, considerably less drainage is predicted (75 mm or 9% of water input) (Figure 1.5.7b). This drainage is due to rainfall occurring during the season and is greater than for dryland cotton, due to rain falling on soil wet by irrigation. This provides a leaching fraction for maintaining the soil salt balance, even though irrigation is not causing drainage.

With no irrigation (dryland cotton), drainage was 6 mm (1%), run-off 16 mm (3%) and ET 589 mm (96% of rainfall).

Figure 1.5.7 Average annual water balance (deep drainage, run-off and evapotranspiration) calculated using the calibrated GLEAMS model (Connolly et al. 1998, 1999) for an Emerald black vertosol, EIA, (a) furrow-irrigated cotton, with typical irrigation, and (b) with reduced irrigation amount.



Furrow advance water balances (Smith et al. 2005)

Analysis of furrow advance data for 79 furrow irrigation events conducted by growers in southern Queensland found average deep drainage losses of 42.5mm per irrigation and potential annual losses of up to 250 mm (Smith et al. 2005). The represents an annual loss of up to 250 mm (2.5 Ml/ha) of water that could be beneficially used to grow more cotton. The same methodology was used to estimate application efficiencies (percentage of water applied that infiltrated into soil) for each irrigation. Application efficiencies were shown to vary widely from 17 to 100% and on average were a low 48%.

"Simulations of each event using the simulation model SIRMOD illustrated simple 'recipe' strategies that would lead to gains in efficiency and reductions in the deep drainage losses. Additional simulations of selected events showed that further significant improvements in performance can be achieved by the application of more advanced irrigation management practices, involving infield evaluation and optimisation of the flowrate and irrigation time to suit the individual soil conditions and furrow characteristics. Application efficiencies in the range 85–95% are achievable in all but the most adverse conditions. The dependency between deep drainage and irrigation management was demonstrated, confirming that substantial reductions in deep drainage are possible by ensuring that irrigation applications do not exceed the soil moisture deficit."

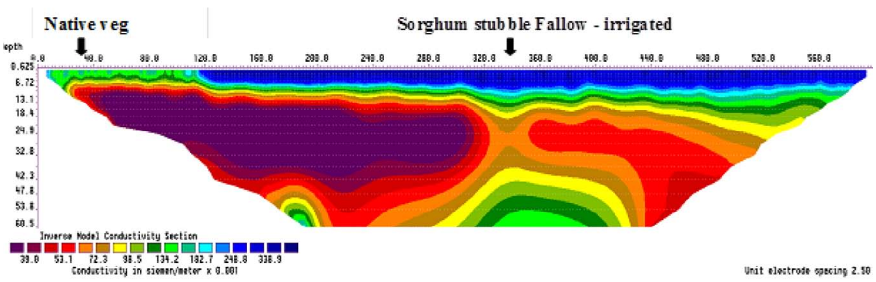
Observed groundwater responses

It would be expected that deep drainage losses occurring under irrigated cropping should create greater groundwater recharge. But this is often not detected in changes to groundwater levels. It may be filling a historic moisture deficit in the unsaturated zone (between the root zone and the groundwater surface) and is therefore not yet causing greater recharge to groundwater. If so, how long before this moisture deficit 'buffer' is full and deep drainage becomes groundwater recharge?

A recent project (Silburn and Foley) investigated two-dimensional transects through native vegetation and adjoining irrigated paddocks to look at historical changes in water and salt fluxes due to land use change. Geophysical surveying methods and deep coring (six to 20-metres deep) were used to look at the moisture status in the deeper regolith/unsaturated zone. Electrical resistivity tomography (ERT) was used to take two dimensional 'snapshots' of the underground landscape. The resistivity measurements tell us a great deal about the amount of salt, water and clay at any point in the deeper profile (up to 60 metres deep). When used in combination with deep coring and soil analysis these elements can be isolated and geophysics models improved.

ERT images were collected along transect lines in both irrigated and uncleared landscapes throughout the Condamine and Border Alluvia's (see Figure 1.5.8). Transects imaged from naturally vegetated landscapes into irrigated paddocks found all soils under native vegetation to be very dry even when only sparsely populated by trees. In contrast, significant long-term migration of deep drainage was evident to deep within the regolith (up to eight to 15 metres) in most irrigated paddocks

Figure 1.5.8 – ERT transect running from native vegetation into fallow irrigated paddock in the Central C ondamine Alluvia (tail drain at 120 m). Blue colour indicates highly wet and conductive clay layers.



Deeper coring with a Geoprobe and coring to four to six metres with the soil coring rig has provided considerable data to support the widespread occurrence of a historic change in regolith water storage as a result of deep drainage under furrow irrigation.

A layer of near-saturated soil in the profile between two to six metres was found in nearly all irrigated paddocks. These wet layers in the profile would not be a static store of irrigation waters, but would be draining into the deeper regolith at a rate proportional to the conductivity of the deeper clay and sand layers. There is tremendous potential to capture and use this currently under-utilised water.

Deep coring in native vegetation sites close to the irrigated sampling sites confirmed the dryer soil profile under native vegetation. In the extensive buffer of dry soil historically in the regolith under trees there is virtually no deep drainage as trees are able to able to extract more water from the soil and to extract water deeper in the profile.There are a number of additional reasons to suggest why rising groundwater levels may not be evident in all areas. In southern and central Queensland, the situation can be summarised as (NR&M salinity and groundwater staff):

Data available

Historically, drilling focused on finding good quality water, and monitoring has focused mainly on sustainable water use from these pumped groundwater areas.

Data are limited outside pumped areas, and data from within these areas is often from pumped aquifers. Data are very limited for shallow aquifers, particularly as drilling for water production would typically exclude shallow, low yielding or poor quality layers, such as salty layers.

Groundwater trends

Groundwater levels have a mixture of rising, falling and steady trends in most regions, with local influences often overriding regional trends.

- Groundwater levels are mostly falling in the Callide, the Upper Condamine Irrigation Areas and the Lower Namoi, due to groundwater pumping.
- Hot spots of rising groundwater occur around the Darling Downs, Border Rivers, St. George, Theodore and Emerald irrigation areas – that is, there is some coincidence with irrigated, non-pumped areas. Free et al. (2001) found groundwater closer to the surface near irrigation than in non-irrigated areas in the Border Rivers.

Response time

An increase in drainage below the root zone is not immediately transmitted to the watertable. Walker et al. (1985) found that, in the western Murray Basin, increased drainage due to clearing of mallee takes 50 to 500 years to increase the recharge of watertables >30 m deep, depending on drainage rate and soil type.

Response time is shorter where drainage rate is higher, depth to watertable is shallower and non-water filled porosity is lower. To illustrate this:

- If moisture storage capacity is 10% (0.1 v/v), the material holds 100 mm of 'new' water per metre depth. (v/v is a unit of water storage capacity, i.e. volume of water storage capacity per unit of total volume).
- With drainage of 10 mm/yr, the new wetting front advances at 0.1 m/yr, reaching a watertable 10 m down in 100 years.
- If drainage rate is 100 mm/yr, the wetting front advances at 1 m/yr, taking 10 years to reach a 10 m deep watertable.

Lateral flow

Some draining water may flow laterally and not reach the watertable directly below where it started. This would require a lateral gradient, and for water to be perched on a less permeable layer between the bottom of the root zone and the watertable.

Recharge refers to drainage that actually reaches the watertable.

Groundwater discharge and pumping

Water is lost from groundwater as discharge (leakage to other groundwater systems or surface streams) or pumping or both.

If the aquifer is losing water faster than the input from recharge then the watertable will fall rather than rise.

Some areas of irrigated cotton coincide with pumped groundwater systems and have falling trends, while other areas of irrigated cotton production and dryland cropping are in areas of little or no groundwater pumping (Gordon 2000), for example the Border Rivers and Lower Balonne.

Multiple aquifer layers

Groundwater systems and their responses to increased recharge are further complicated by the fact that below the root zone there will be layers of varying hydraulic conductivity, porosity, geology and states of decomposition and fracturing.

Saturated layers (aquifers) can occur at various depths. Excessive deep drainage can be causing a watertable to rise in a shallow layer, while pumping is causing depletion of a deeper layer, and all of these layers can be receiving or discharging water laterally.

Proportion of area irrigated

Only a small proportion of any catchment is irrigated, for example less that 1% of the Condamine-Balonne, and not all areas developed for irrigation are irrigated in any one year.

However, in a particular subcatchment or groundwater system (e.g. alluvial valleys), the proportion of area irrigated can be larger. Also, if the drainage rate under irrigation is large compared to other land uses, the contribution from irrigation can be large even though the area is small (Vervoort et al. 2003).

Recent drilling in non-production areas (Free et al. 2001; Ed Power, NRM&E, pers. comm.) indicate significant areas of alluvial plains in the QMDB have watertables at depths of, for example, 10 to 20 m, with high to very high salinity (14,000 to 45,000 EC units). No trend data are available as yet.

How can deep drainage be 100–200 mm/yr?

The review of deep drainage studies indicates that drainage ranges from 3 to 900 mm/yr (0.03 to 9 ML/ha) and is often 100 to 200 mm/yr (1–2 ML/ha). This is surprisingly high considering the long-held view, described in the introduction, that 'clay soils don't drain'. Here three factors that might limit drainage are considered: soil infiltration rate (or hydraulic conductivity), soil drainable porosity and the balance of water supply relative to evapotranspiration.

Simple drainage estimate 1: low infiltration rates

Say the final infiltration rate under irrigation is 1 mm/hr (that is, 24 mm/day). This is about the upper limit for long-term infiltration rates, that is, with 3 to 7 days of ponding, of Shaw and Yule (1978) and Gardiner and Coughlan (1982), but is generally below the infiltration rates measured after 5 hours of ponding, by which time soil water deficits were replenished.

- With this infiltration rate through wet soil, only 8 days that have a wet profile are needed for drainage of 200 mm/yr. That is, 1 mm/hr × 24 hrs× 8 days (say 6 irrigations and 2 large rainfall events) = ~200 mm/yr.
- Conclusion: 1 mm/hr is not that low – drainage of 200 mm/yr is quite likely.

If drainage is 1 mm/day, which is at the low end of the range of long-term infiltration rates of Shaw and Yule (1978) and Gardiner and Coughlan (1982), for example, a soil with a sodic subsoil (ESP >25) (Shaw 1995):

- If drainage occurs for 3 days after each of 6 irrigations and 2 rainfalls, drainage = 1 mm/day × 3 days × 8 events = 24 mm/yr. This is consistent with drainage data from sodic grey clays, presented above.
- However, if the subsoil below the root zone is saturated after each irrigation, and drains for, say, a total of 100 days, drainage is 100 mm/yr. Data presented below (Figure 1.5.3) indicates that the subsoil can be near saturated through the entire irrigation season.
- Thus, even 1 mm/day drainage rate will result in considerable drainage if there are many days of drainage.

Simple drainage estimate 2: drainable porosity

Drainable porosity is the volume of water that can be stored in the volume of soil and which is able to drain after each wetting event. Gardiner (1988) showed that, for clay soil profiles, drainable porosity is 0.03 to 0.07 v/v.

If we take 0.03 v/v × 1000 mm soil depth = 30 mm of drainable water per wetting; for 7 wetting events = 210 mm that drains eventually, if it is not used in ET before it can drain. Thus the low drainable porosity of clay soils will not prevent drainage at the annual rates observed.

Simple drainage estimate 3: approximate water balance

Drainage is limited if evapotranspiration (ET) uses the rainfall and irrigation water. A water balance (Table 1.5.8) based on available data indicates that typical rainfall and irrigation is sufficient to allow drainage of 200 mm/yr. Various factors can be adjusted up or down by, say 50 mm, but water in excess of ET must go somewhere.

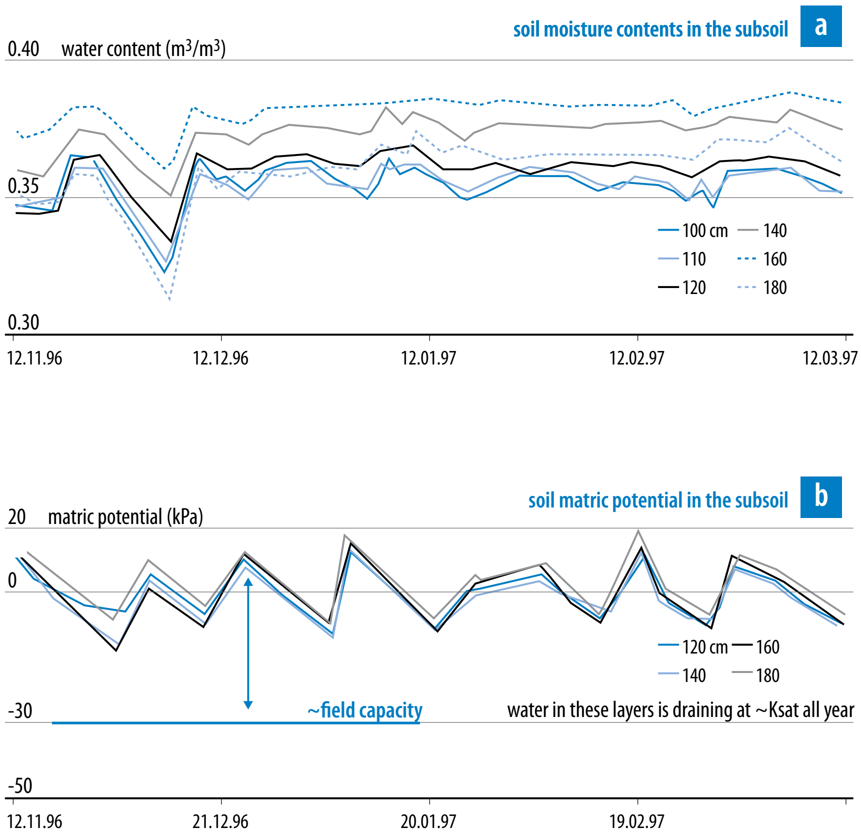
Table 1.5.8 A simple average water balance for a cotton crop season

Component		Water (mm)	Source
Water inputs	Rain	400	⅔ of a 600 mm annual rainfall
	ΔSW	50	25% storage of 200 mm winter rain
	Irrigation	700	7 ML/ha, Hearn (1998)
	Total	**1150**	
Water outputs	ET	−800	Steve Milroy, ACRI; Hearn (1998)
	Excess	350	
	Run-off	−150	Silburn et al. (1997, 1998)
	Drainage	**200**	by difference

Don't get fooled by constant subsoil moisture contents!

In the past, emphasis has been put on constant subsoil moisture content as evidence of no drainage. Figure 1.5.9a is an example of such data from a grey vertosol in the Gwydir valley.

Figure 1.5.9 (a) Soil moisture in subsoil layers of a grey vertosol (Gwydir) through the irrigation season (b) Soil matric potential in the same layers, indicating near saturation (zero matric potential) throughout.



All layers from 100 to 180 cm show fairly constant moisture contents in the range 0.35–0.38 v/v which would seem like a somewhat moderate water content. However, with a bulk density (BD) of 1.59 g/cc, total porosity (TP) is 0.40 v/v (with a BD of 1.7, TP=0.36), so a water content of 0.38 v/v is in fact near saturation. We expect drained upper limit (DUL or field capacity) to be about 0.05 v/v below TP (typical air content in clay subsoils at drained upper limit, Gardner 1988), that is, DUL=0.35 v/v.

Thus, the measured subsoil moisture contents are likely to be between drained upper limit and saturation, and some soil water is drainable. This is confirmed by tensiometer data (soil matric potential) from the subsoil (Figure 1.5.9b), which indicates that all layers between 120 and 180 cm were at or near saturation throughout the irrigation season. (Roots appear to have penetrated to about 100 cm.) Thus, water was probably **draining through the subsoil** throughout the season. Water balance measurements at the site indicated that 158 mm drained below 180 cm during the four irrigation periods monitored (Table 1.5.7).

Conclusions

Studies (up until about mid-2012) of drainage below the root zone (deep drainage) in irrigated cotton fields in the Northern Murray–Darling Basin and central Queensland were reviewed. These studies indicate that:

1. Deep drainage varies considerably depending on soil properties and irrigation management, and is not necessarily 'very small', as believed in the past.
2. Deep drainage of 100 to 200 mm/yr (1–2 ML/ha) is typical, although rates of 0 to 900 mm/yr (0.03 to 9 ML/ha) were observed.
3. These drainage rates are compatible with clay soil infiltration rates, drainable porosity and with water balance (water applied, run-off and ET).
4. Near saturated conditions can be found in the soil two to six metres below irrigated fields. Such conditions have not been found to occur under adjacent native vegetation, indicating a considerable store of historical drainage.
5. Drainage can occur through the soil matrix (matrix drainage), or through soil cracks (bypass drainage) when furrow irrigation occurs.
6. Some drainage, or leaching fraction, is needed to avoid salt build-up in the soil profile, although this should largely be provided by rainfall except where irrigation water quality is poor (for example, some bore waters).
7. Deep drainage under irrigated fields may have decreased over the past decade as awareness of deep drainage as an issue has increased and furrow irrigation management has improved.
8. Furrow irrigation should be managed to minimise the time available for infiltration by getting water on and off quickly. As much of the seasonal deep drainage can occur early in the season, irrigation management at this time is critical.
9. Increased salinity in the water used for irrigation (from streams and groundwater) is a threat to the irrigated industry.
10. Soils used for irrigated cotton are more diverse than 'clay soils', with a wide variety of properties and management requirements.
11. The consequences of deep drainage are distinctly different where underlying groundwater can be used for pumping (fresh water, high flow rate) and where it cannot (saline water or low flow rate); significant areas of irrigation occur on groundwater areas of both classes.

Acknowledgments

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Further Reading

Deep Drainage Myth Busters

Final Report (McGarry and Gunawardena) – Deep Drainage Under Irrigated Cotton – Surface and Groundwater Implications

Final Report (Ringrose-Voase) – Quantifying Deep Drainage and its Contaminants Under Irrigated Cotton

Final Report (Silburn and Foley) - Soil Water Balance and Deep Drainage Under Irrigation

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1.6 Managing storages and channels

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Key points

- Storages are the largest source of water loss on most irrigated cotton farms.
- Measurement is critical for determining storage losses. Even if you think your losses are low, this information is very important for water budgeting and benchmarking.
- Storages can differ from their design volume by 20% or more. Storage surveys are very useful to verify storage capacity and storage curves.
- A range of solutions for minimising evaporation and seepage can be employed ranging from management options to structural solutions.
- The evaporation and seepage ready reckoner can be used to determine the cost effectiveness of different solutions

Whole farm water use efficiencies are reduced by excessive evaporation or seepage losses, or both, while water is being stored in dams, conveyed around the farm, applied to fields or returned to the storage. This topic considers the opportunities for measuring evaporation and seepage losses from storages, channels and reticulation systems, investigating potential solutions for remediating excessive losses and assessing whether these solutions can be economically applied.

Determine the extent of losses

The first step when considering ways to minimise losses from storages is to get as much information about the actual loss that is occurring. This is absolutely necessary in order to determine the best possible solution, how effective it might be and how cost effective it is to implement. Much of this information is also valuable for other purposes in farm water management and planning.

Regular recording of water depth and volume

Regularly recording water depth and volume provides excellent information for general water management but can also highlight potential issues and changes in storage performance over time. An up to date storage volume record can improve forward decision making about planting area or how to best use the available water during the irrigation season. Accurate storage volume data is required when preparing water budgets and regular data is required to be able to update budgets throughout the season.

Importantly for understanding losses, storage volume information allows you to perform a whole farm water balance which can reveal how significant storage losses are as a proportion of all on farm water loss. Regular information which can provide you with data on the volume of water extracted from and returned to storage can also allow you to calculate storage efficiency.

Whole farm water balance

A whole farm water balance is a procedure by which the water inputs and outputs of a farm are compared so that losses can be determined. Recently developed tools such as Watertrack Divider™ allow the losses from different components of the irrigation system (storages, channels, drains and fields) to be determined. Further information on whole farm water balance can be found on page 51 of the 2012 Australian Cotton Production Manual.

Such an assessment can reveal the significance of storage losses as a component of all on-farm water use which can help to prioritise areas where effort to reduce losses should be targeted. Measures of storage volume are required for these calculations.

An assessment of water losses for 30 farms in the Queensland Murray Darling Basin for the 2009-10 and 2010-11 seasons showed that storages were the greatest source of loss. Whilst the average storage loss was 20% (Figure 1.6.1), individual farms had losses ranging from about 5% to 45% (Figure 1.6.2). A full summary of results is available in the publication Whole Farm Water Balance: Summary of Data 2009-2011.

Figure 1.6.1 – Average water use for 30 farms in the QMDB 2009-2011.

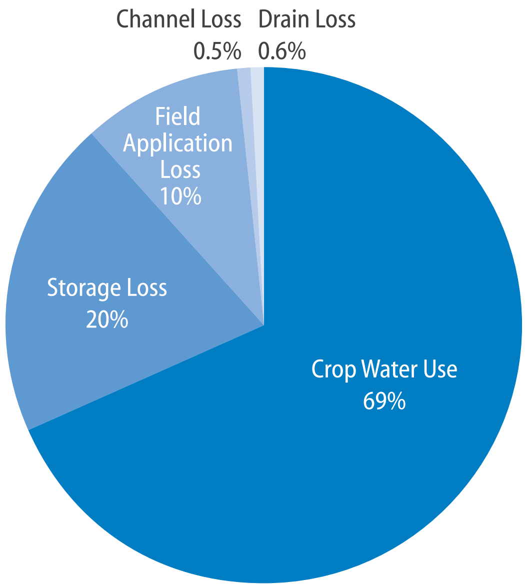
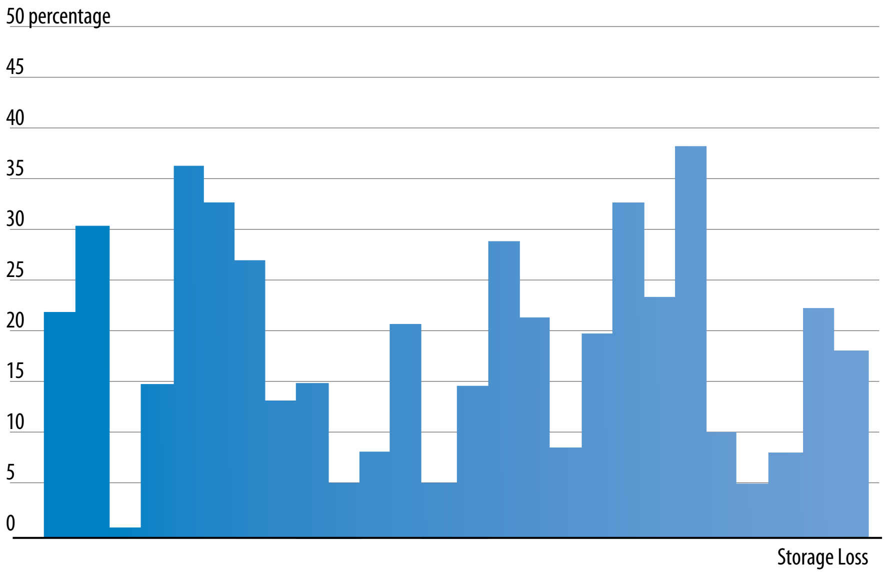


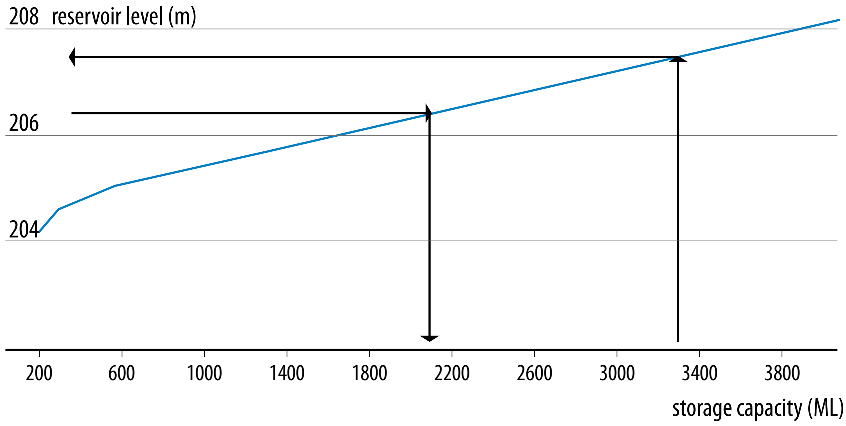
Figure 1.6.2 – The range of water lost in storage for individual farms in the QMDB 2009-2011.



Measurement techniques

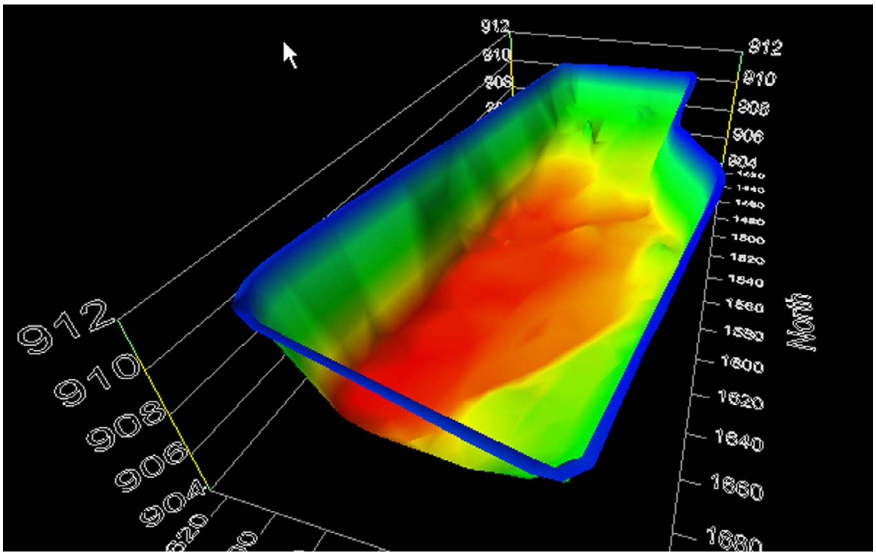
Most storages have gauge boards which give a visual indicator of storage depth. Gauge boards can provide a measure of the amount of water in storage, although converting this water depth to a volume requires a storage curve. Engineers produce storage curves for each dam they build. Storage curves relate the volume of water stored or storage capacity in mega litres to the height of the water in the dam. The height of the water is usually recorded as its height above sea level. Figure 1.6.3 shows how a gauge board level can be converted to a volume (and vice versa) using a storage curve.

Figure 1.6.3. Flow meters with gauge boards and storage curves



Whilst manual recording of gauge board levels can provide some information, regular information (for example daily or hourly) is usually required to determine the inflow and outflow volumes needed to calculate storage efficiency. Alternatively, flow meters may be able to provide this information, although they do not provide a measure of the volume of water in storage at any one time.

Figure 1.6.4 – An example of a modern storage survey.



Electronic storage meters (such as the Irrimate Storage Meter™) have become more popular in recent years as they provide a real time measure of the volume of water in storage and can be fitted with telemetry systems so that this information can always be available in the farm office. This information can be used for whole farm water balance, real time water budgeting and calculating storage efficiency.

Storage survey

A storage survey is another particularly useful piece of information to better understand your storage. Usually the storage curve will have been determined when the storage was originally designed. In recent years, advances in surveying techniques have allowed much more detailed information to be obtained in shorter timeframes and the number of growers obtaining storage surveys has increased. Storages can even be surveyed when they are full of water!

However many of these storage surveys have revealed inaccuracies in the original information, with the actual volume of some storages having a difference of more than 20% when compared to the existing information used by the grower. This has significant implications for management decisions and water budgeting, where such inaccuracies could mean that water runs out prematurely or water that could have been used productively is not required. Furthermore, such errors could be masking substantial storage losses.

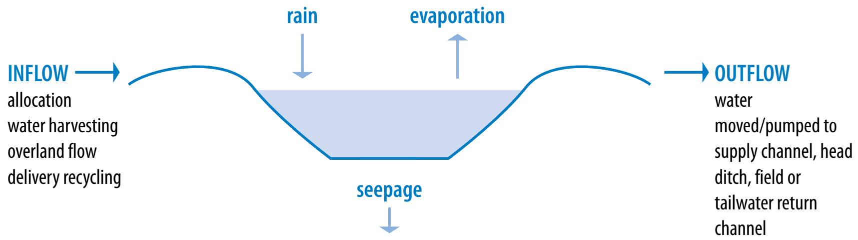
Storage Efficiency

Like other measures of irrigation efficiency, storage efficiency relates the amount of water used to the amount of water supplied (stored) over a period of time.

$$\text{Storage Efficiency} = \frac{\text{water used from the storage}}{\text{water stored in the storage}} \times 100$$

The same calculation can also be used to determine the efficiency of channels and return systems. Because these systems usually have water being added and removed regularly, obtaining the actual water used and stored over a period of time can be difficult. This typically requires regular readings from flow meters or a regular measure of total storage volume to be able to determine the water inflows and outflows. All of these systems have a similar set of inputs and outputs, as shown in Figure 1.6.5.

Figure 1.6.5. Components of the water balance of storages, channels and return systems



Source: Dalton et al. 2002

From this, it can be seen that the information required to calculate efficiency in the equation above is as follows:

Water used from the storage = Water outflow – tailwater return

Water stored in the storage = Starting volume + water inflow + rainfall – ending volume

If all of the required parameters have been accurately measured, the difference between the two terms will account for the storage losses (seepage and evaporation).

Dalton (2000) demonstrated how the duration of water storage can affect storage efficiency with measurements on a storage with two cells that were both filled at the start of the season. Water from one cell was used early in the season for pre-irrigation and had a storage efficiency of 85% while the other cell was used for later irrigations and had a storage efficiency of 55%. Channel efficiencies should be higher than for dams because water is not usually stored for long periods of time before it is used and this reduces the opportunity for evaporation and seepage to occur.

Seepage and evaporation measurements

Regular storage volume data and a better understanding of storage capacity are particularly useful for better water management and to identify the magnitude of storage losses within the context of all farm water use. However, if this information suggests that options to reduce storage loss should be investigated, it is important to know how this storage loss is occurring, and therefore what type of action would be most appropriate.

Storages can lose water through either seepage or evaporation, but it has historically been difficult to determine what proportion each contributes to the total loss. In practice, this has often been achieved by estimating evaporation losses (for example by using ET_0 or pan data) and subtracting this from the total water loss to provide an estimate of seepage. The Ready Reckoner Monthly Evaporation Calculator can be used for this purpose.

However it is now known that evaporation from individual storages can vary due to local characteristics such as the shape and dimensions of the storage or the nature of the surrounding area, which can influence the fetch (the upwind conditions). Other characteristics such as the temperature of the water will also affect evaporation. This means that evaporation estimates should be multiplied by a dam factor (k_{dam}) before they are accurate for a particular storage, although unmodified evaporation data is still better than nothing.

Recent work has been undertaken by a number of organisations across Australia to better understand the nature of seepage and evaporation losses. From some of this work, equipment and data analysis techniques were developed to obtain these measurements in a more practical way. This is now provided as the Irrimate™ Seepage and Evaporation Meter.

It should be noted that existing research techniques, such as atmospheric flux techniques (for measuring evaporation) or infiltrometers (for measuring seepage), rely on point source measurements and do not give a value for the entire storage. The Irrimate™ Seepage and Evaporation Meter measures losses from an entire storage, which is especially important considering most seepage loss tends to occur in discrete locations rather than uniformly across an entire storage.

Once you have measures of evaporation and seepage, they can be used to:

- Improve the accuracy of detailed water budgets and whole farm water balances.
- Compare losses from different storages to identify which (if any) require attention.
- Determine whether seepage or evaporation is the main issue that to be addressed.
- Determine the cost effectiveness of potential solutions.

The use of this data for determining the cost effectiveness of different solutions is covered later in this chapter.

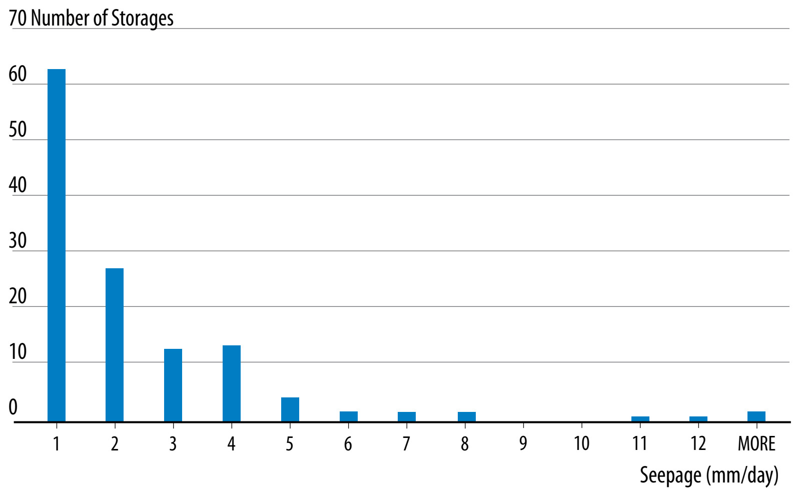
However this case study demonstrates how valuable this information can be for water budgeting. In this case, the grower undertook a water budget and estimated that the seepage loss from this storage was 1 mm/day. When measured, the actual seepage loss was 3.5 mm/day. Although this loss is still reasonably low, it meant that the water budget was underestimating the actual seepage loss by 50 ML per month!

For storages where seepage losses are very high (greater than about 10 mm/day), an initial rough estimate of losses may still be useful to determine whether the seepage loss is so high that you should consider immediate action (possibly even removing the water from the storage as soon as possible). Manually measuring the total storage level change over a period of a few weeks and subtracting the evaporation data for this period can provide you with an estimate of seepage. However an accurate measure is still required to determine the cost effectiveness of potential solutions with any certainty. Furthermore, losses less than 10 mm/day are still significant, but are much more difficult to measure with any accuracy. As an accurate measurement can take about 5 weeks to obtain, the longer the delay in deploying this equipment, the longer water must remain in the storage.

Existing Industry Data

The Irrimate™ technology was used to measure seepage and evaporation losses from 137 storages across the cotton industry from 2009 to 2011. The storages ranged from 75 ML to 14000 ML in volume and had depths of water at the time of measurement from 1 metre to 9 metres. Seepage for most storages was generally quite low, with 88% of storages having a seepage rate of less than 4mm/day (Figure 1.6.6). Growers were asked to estimate their seepage rate as low, moderate, high or very high prior to the evaluation taking place. Only 80% of growers were able to accurately estimate their seepage rate within these broad bands. This highlights the value of accurately measuring seepage to ensure that your whole farm water management and budgeting is accurate.

Figure 1.6.6 - Number of storages measured with seepage of different rates



Evaporation was also measured and a dam factor (k_{dam}) was developed for each storage which related the actual evaporation from the storage to the predicted FAO56 ET_0 value at each location obtained from the SILO service.

Daily evaporation (mm) = k_{dam} x SILO Daily Et_0 (mm)

Dam factors ranged from around 0.7 to around 1.3 (Figure 1.6.7), indicating that individual storages could have quite different evaporation rates. This would be due to various individual characteristics such as the water temperature, the orientation of the dam to prevailing winds and the presence of windbreaks, amongst others. This potential annual evaporation ranged from 1 to 2 metres per year (Figure 1.6.8) depending on the storage location (high evaporation environment vs. low evaporation environment) and the individual dam factor. The average potential evaporation was around 1.5 metres per year.

Figure 1.6.7 - Number of storages with different dam factors (k_{dam})

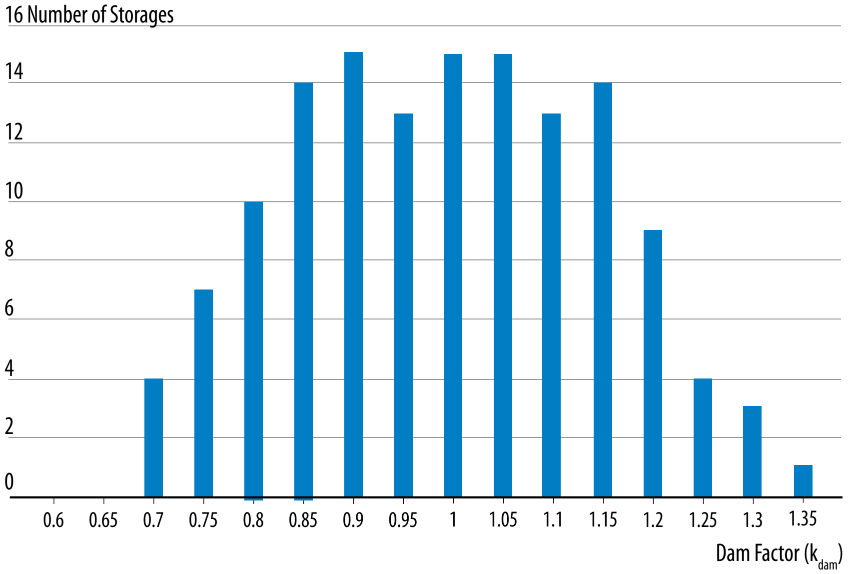
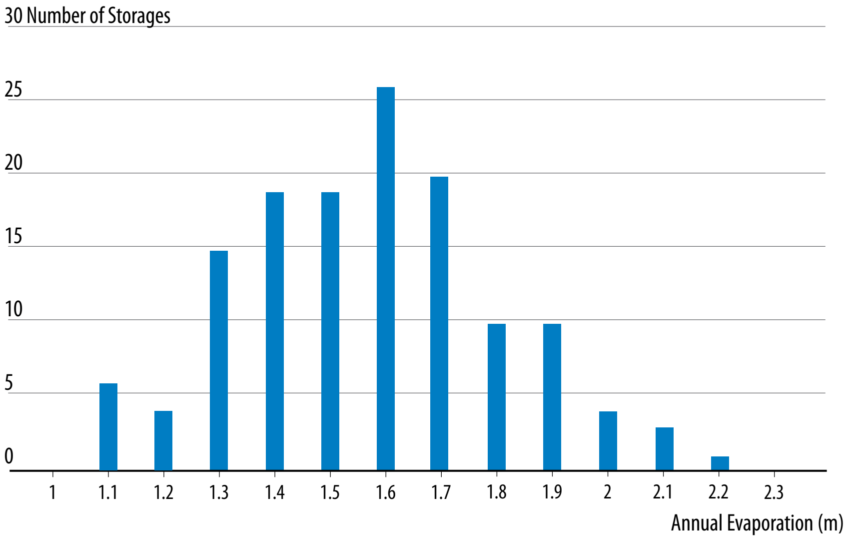


Figure 1.6.8 - Number of storages with different potential annual evaporation



Identify potential solutions

If you have undertaken the various measurements outlined above, you will be in a good position to determine whether or not the losses from your storage require attention. Whether or not you should actually take action will ultimately be determined by the cost effectiveness of particular solutions; methods for determining cost effectiveness are outlined later.

If you have undertaken a whole farm water balance, there are unfortunately no hard and fast rules regarding how much storage loss should be expected, except to say that lower is obviously better.

The proportion of water lost in storage will vary depending upon the nature of your water supply. Those growers who need to store water for long periods of time will most likely have a greater proportion of loss than growers who reduce their storage volume quickly. The best way to use this information is to compare with other growers who have similar operations to your own.

If you have seepage and evaporation measurements, you may be able to compare your results to those obtained from the industry study above. In terms of evaporation, the longer you store water, the more cost effective it will be to apply an evaporation mitigation strategy. Recent investigations have shown that some strategies such as dividing a storage into cells can be very cost effective as discussed below.

In terms of seepage, the seepage rate at which it becomes cost effective to take action will vary significantly depending upon how often your storage contains water, the area over which seepage is occurring, the effectiveness of potential remedies and the cost of these remedies. Table 1.6.1 contains a very rough guide

Table 1.6.1 – A rough guide to storage seepage rates.

Seepage Rate	
Above 3 – 4 mm/day	If you store water fairly regularly, it may be cost effective to undertake remediation works, provided the seepage is occurring in a confined area and the potential remedies provide effective seepage reduction. If this is not possible, at least having a precise measure of your seepage rate will be invaluable for water budgeting.
Above 6 mm/day	Numerous seepage remedies are likely to be cost effective, provided you can identify where the seepage is occurring and the applicable remedies are able to provide effective reduction in your circumstances.
Above 8 mm/day	You really need to take action. Most remedies will be cost effective. You will still need to be able to identify where the seepage is occurring and have conditions under which the mitigation solution will be effective. At these seepage rates it is probably advisable to use the storage as little as possible.

The following sections will outline the potential options that may be considered and their likely effectiveness. The cost effectiveness of the most suitable option, and therefore the final decision about how to act, is covered in the final section.

Management solutions

Perhaps the lowest cost solution available is to focus on managing the water that you have. The flexibility you have will be limited by your farm characteristics, but management options would include combining water from multiple storages into a single storage, moving water from a partly full large storage into a smaller storage or applying water to fields in preparation for the next season's crop. Each of these options is aimed at reducing the surface area of water that is available to be evaporated or to be lost to seepage.

A simple calculator which predicts the likely monthly volume of evaporation and seepage loss for a given surface area is available on the Evaporation and Seepage Ready Reckoner website. It should be noted that this calculator does not account for individual dam factors and provides only an estimate of evaporation based on historical averages.

Moving water

Moving water between storages might be attractive when you have small amounts of water in two or more storages, or when you are holding water in a storage which is larger or has higher losses than an alternative storage. When you move water between storages, you should consider:

- The water required to saturate the floor of the storage you are moving water to. If the floor of this storage is particularly dry, you could lose up to 2.5 ML/ha of water to wet the floor up.
- Seepage and evaporation in the channel you use to move the water. This includes the water required to wet the channel up if it is dry. On-farm channel losses are generally reasonably small, with seasonal channel losses amounting to less than 2% of total farm water.
- The difference in loss between the existing scenario and the proposed scenario.
- The cost of moving the water.

This case study illustrates how one grower determined the cost effectiveness of stacking water from 3 storages into 2 storages. In this case the grower had three storages that were partly full. One of these storages contained about 1500 ML and there was sufficient space in the other two storages to empty this storage. The grower had measured the seepage and evaporation loss of his storages using the technology discussed above, so he knew that his seepage loss was 2.9mm/day. He could also apply his dam factor to the average evaporation figures for the next three months that he needed to store the water.

The potential water lost by leaving the 1500 ML in the current storage for 3 months was calculated to be 640 ML. As the other two storages contained water anyway, there was negligible change in storage loss from these storages. Similarly, there were no significant channel losses as the storages were very close together and the channel was already wet.

The cost of pumping the water was estimated at $10 per ML (10 L of diesel at $1 per litre) so the total cost was $15,000. As the amount of water saved was 640 ML, the cost per ML was $23.40 which was much cheaper than purchasing this water from elsewhere.

Note that a pump test could provide this grower with an improved measure of the true pumping cost.

Applying water to a field

In some circumstances, it might be worth considering applying water to fields rather than keeping the water in a storage. It might be possible to plant an opportunistic crop which could use this water as soon as possible, although in many circumstances this strategy will be used to apply water to fallow fields. This would be an attractive option when:

- The volume of water in storage is small, and it is likely to be lost before it can be used
- There is no alternative storage in which the water can be put.
- The storage has very high losses and the water will be rapidly lost.

There are still a number of factors that should be considered:

- By applying water to the field you may reduce the ability for the field to capture upcoming rainfall. If it does rain, you may still be able to capture this water as excess runoff, but you will now have to pay to pump it into the storage. This should be considered if the probability of rainfall is high.
- Some amount of soil evaporation is likely. Where water is contained in a deep storage with a small surface area, and the field area over which this water would be applied is large (for example if the soil has low moisture holding capacity or already contains substantial moisture) then the benefit of applying the water to fields should be carefully considered.
- Fallow fields should be managed in accordance with appropriate moisture conservation techniques (such as retaining standing stubble and managing weeds).
- Deep drainage research has found that most water is lost early in the season, when soils are likely to be driest (see WATERpak Chapter 1.5). The potential for losing water applied to fields as deep drainage should be considered.

Other options

Wind breaks may also be effective at reducing evaporation by altering the wind speed across the water surface. Trees have often been used for this purpose, although the actual extent of evaporation reduction is not well known. Importantly, the roots of any vegetation will seek out water and they can threaten the integrity of the embankment. Even some grasses have been known to penetrate deeply (up to 9 metres) into storage walls in search of moisture. In addition, vegetation in close proximity to an embankment will make routine embankment access or maintenance difficult.

It is therefore recommended that any vegetation is kept at a reasonable distance from storage walls. It is probably best to have tress at least 15 metres from the toe of the wall. More information on vegetation near storages is available in the Guidelines for Ring Tank Storages.

Some have suggested that floating or emergent vegetation within the storage could be used to reduce the water surface area exposed to open evaporation. However any vegetation, either floating on the surface or emergent deep rooted, will actively transpire and therefore water loss will continue to occur. The vegetation will enhance the surface roughness of the water and may actually enhance water vapour transfer rates compared to the smooth surface of open water. Therefore such practices are not recommended.

Structural Modifications

Storage structural modifications aim to minimise the surface area of water available for evaporation and seepage for a given volume of water stored, thus reducing overall losses. This can be achieved by:

- Splitting a storage into cells. In this case, when the volume of water is low it can be concentrated into a smaller area.
- Raising the height of a storage. In this case, it might be possible to reduce the use of a second storage by concentrating the water into a single, deeper storage. Alternatively, it might be worthwhile moving the wall of an existing storage to decrease the storage footprint but at the same time raise the wall height so the volume of water stored does not change.
- Modifying the storage to remove an area of high seepage.

Divide a storage into cells

Dividing a storage into cells allows it to be better managed to reduce evaporation and seepage losses by concentrating water into a smaller surface area whenever possible. Smaller cells will also reduce wind action. This strategy is particularly useful for reducing losses during periods of low water availability, and storages which often contain small proportions of water are most likely to benefit.

The effectiveness of cells at saving water will depend on the storage water holding pattern and the relative size of the cells. For example a storage which is often 70% full but has two equally sized cells will regularly have water in both cells and therefore savings will be low. Determining the optimum cell proportions is important when considering this strategy. Similarly, the savings from storages which only hold water for a small period of time will most likely be low.

Storages that have been divided into cells will require some additional maintenance of the dividing wall, although this should not be a significant burden. The main consideration in operating cells is how the water is managed and transferred between cells. The ability to extract water from either cell will provide management flexibility. Cells should be able to be drained of all water, as any water remaining in a cell will result in evaporation loss. When managing water between cells, the volume of water that may be lost when wetting up a dry cell should be accounted for. This loss may be up to 2.5 ML/ha for a very dry cell.

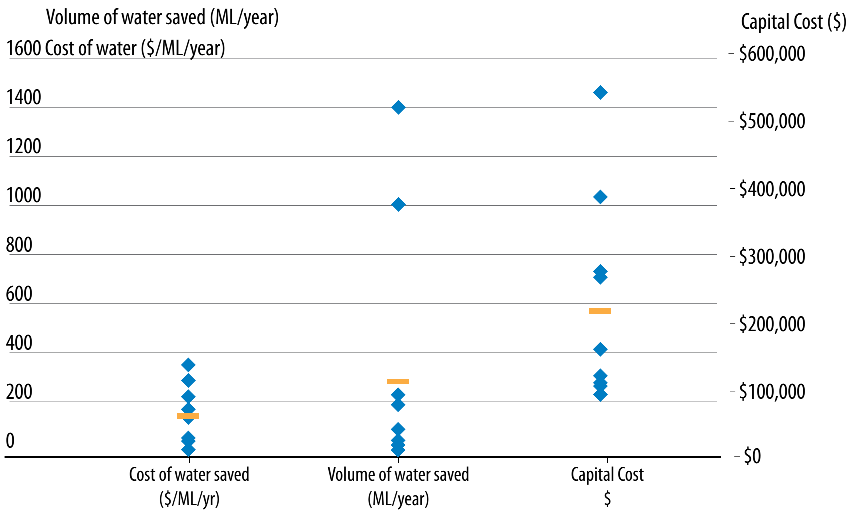
The construction standard of the dividing wall needs to be just as high as for the outside embankments. In this case, however, both batters need to be flat to minimise erosion: at least 5:1 and preferably 8:1.

In addition, the core of the dividing wall needs to be carried through to join the core of the existing outside embankment. That is, the inside batter of the original embankment needs to be removed at the proposed junction, leaving the core exposed. The scrapers should remove some of the existing core to provide a sufficiently flat slope to bond with the core of the dividing wall, by watering and rolling. The original batters are then re-established, joining with the new.

A similar procedure is required if a new, external cell is added to a storage, with the core of the new embankment bonded to the old.

The cost effectiveness of cell division strategies will vary depending upon individual circumstances, although recent evaluation across a number of properties in the Queensland Murray Darling Basin showed that this strategy was cost effective in most cases. As illustrated in Figure 1.6.9, the cost of water saved was generally quite reasonable, with only 3 out of 11 storages having a cost above $200/ML/year. The lowest cost was around $15/ML/year with the highest cost $350/ML/year. The cost of earthworks for cell construction will vary depending upon individual requirements. A cost of $3/m^3 was typically used for these calculations.

Figure 1.6.9 - Results of cell division strategies on 11 storages. Orange markers indicate the mean of all values.



Raise wall height

Raising the height of a storage wall will allow it to hold more water without substantially altering the surface area. Whilst this will provide a better ratio of water loss per ML of water stored, the total volume of loss will still be the same. This strategy is most effective when:

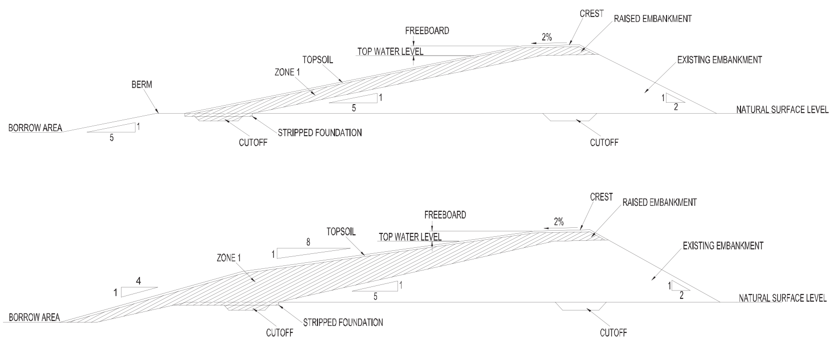
- The total volume of on-farm storage is going to be increased. Increasing the height of a current storage will most likely result in lower losses than building a second storage.
- The walls of one storage are raised so that it can hold water that is currently stored in a second storage. In this case, the losses from the second storage will be saved.
- The wall of a storage is moved to reduce the overall footprint and the height is raised so that it stores the same volume of water.

As with cell division strategies, the water savings will depend on the storage characteristics and the water holding pattern. The finished height of the storage wall can influence the cost of construction and may have regulatory impacts that need to be investigated. There will also be an increase in maintenance costs as the wall area has increased.

Two possible methods of raising the embankment are shown in Figure 1.6.10. In the first figure, the embankment is raised on the original profile (5:1 inside batter). In the second figure, the embankment is rebuilt with an 8:1 inside batter. The second is preferable but requires more fill, particularly if the existing borrow pit needs to be fully or partially refilled. In both cases a new core and cut-off trench is required, backfilled with compacted moist select clay. Foundations need stripping and topsoil is to be replaced. Whilst it might seem attractive to place the new fill on the outside batter, particularly if the storage is holding water at the time, this option should be avoided.

In raising the embankment, exacting design and construction standards are required for the new works, particularly as the construction standard of the original works may be unknown. These standards are outlined in the Guidelines for Ring Tank Storages.

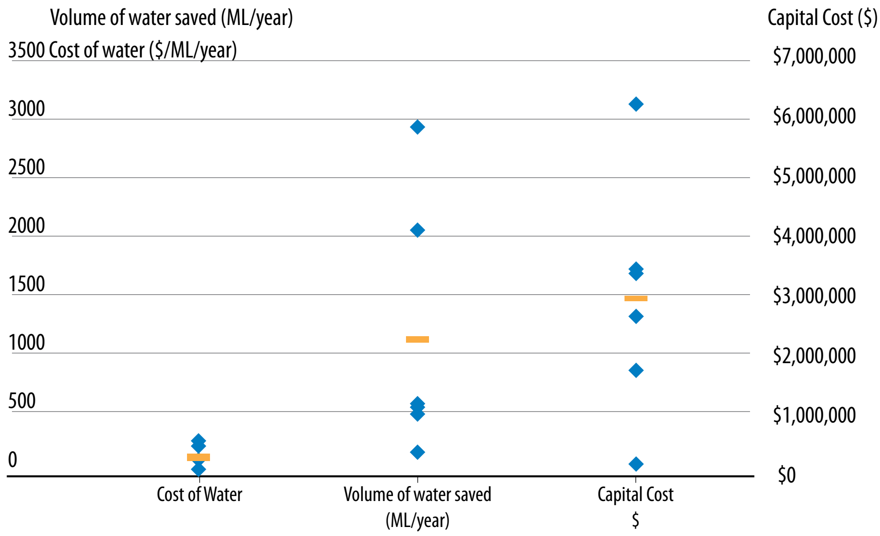
Figure 1.6.10 – Construction methods for raising the embankment of a storage wall. Source: Guidelines for Ring Tank Storages.



The cost effectiveness of raising wall height will vary depending upon individual circumstances. Recent evaluations for six properties in the Queensland Murray Darling Basin showed that this strategy was cost effective in most cases. These scenarios mostly involved raising the height of one storage so that it could fit the contents of a second storage, which could then be decommissioned. One particular scenario involved moving one wall of an existing storage so that the footprint was reduced whilst simultaneously increasing the wall height so the volume stored remained the same.

As illustrated in Figure 1.6.11, the cost of water saved was generally quite reasonable, with only two out of six storages having a cost above $200/ML/year. The average cost of water saved was $169/ML/year, and the cost ranged from $61/ML/year to $300/ML/year. The volumes of water saved were often considerable, although the capital cost was also high. The cost of earthworks used in these case studies was typically $3/m^3 and, where required, the cost of failure impact assessments was usually included. Earthwork costs may increase depending upon the difficulty of work required.

Figure 1.6.11 - Results of wall height strategies on 6 storages. Orange markers indicate the mean of all values.

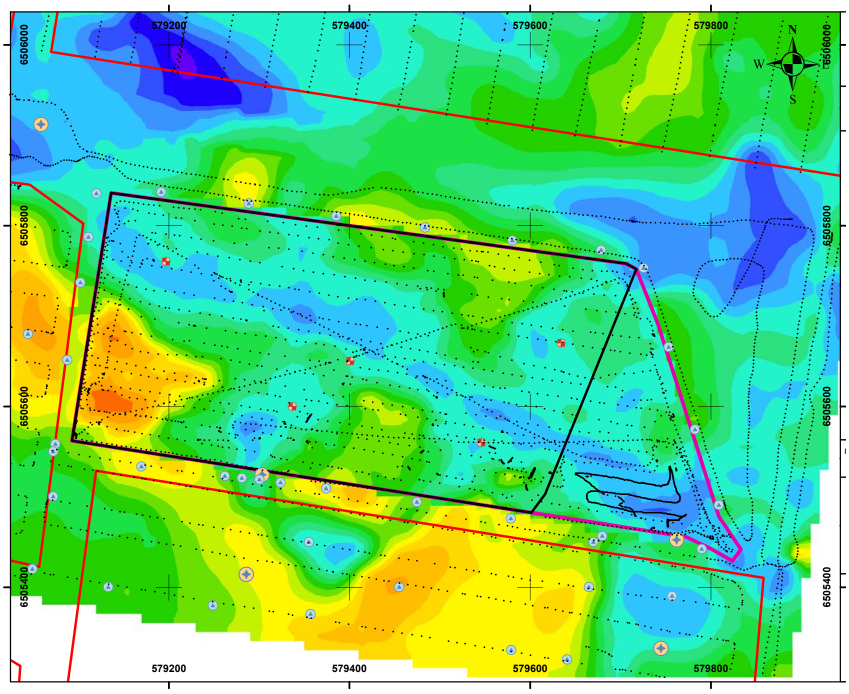


Modify storage shape

In some cases, modifying the position of a storage wall can be a useful way of excluding an area in which seepage is occurring. As such a modification will most likely reduce the volume of the storage, it is important to be sure that the area which is being excluded is the source of the seepage and that the entire area at fault is being removed. There would be nothing worse than spending money on building a storage wall to find out that the storage still leaks! A case study of a grower who moved a storage wall to exclude an area of high seepage is included in a publication of Seepage Remediation Case Studies.

In this case, the corner of a storage was thought to be leaking and causing most of the seepage loss within the storage. The seepage was also affecting a portion of a nearby field, causing waterlogging. A soil specialist was called in who determined the extent of the area that was causing the problem and a new wall was designed so that the offending area could be removed from the storage.

Figure 1.6.12 – An EM survey was one of the techniques used to diagnose the leaking area of the storage, shown in blue in the bottom right hand corner.



Evaporation

Solutions particularly aimed at reducing evaporation generally revolve around applying some form of barrier or treatment to the water surface. There are a wide range of products available for controlling evaporation, which broadly fall under the following categories:

- Continuous floating covers
- Modular floating covers
- Suspended structures (shadecloth)
- Chemical covers

Key factors when selecting these products are the effectiveness of the solution, the capital and operating costs involved, the impact on water quality and dam safety. Uptake of these products in the cotton industry has largely been limited by cost effectiveness.

Those products that are very effective also tend to be high cost whilst those products which are low cost tend to have poor or variable performance. An analysis of the strengths and weaknesses of a range of evaporation solutions is available online. Ongoing research is attempting to make these solutions more cost effective.

Continuous floating covers

Continuous floating plastic covers act as a physical impermeable barrier that floats on the water surface and can achieve above 90% evaporation savings for full cover of the dam. Many different materials have been trialled in the past including wax, foam and polystyrene, but polyethylene plastic has proved to be the most satisfactory and durable material for covers of this type.

Figure 1.6.13 shows a newly installed floating cover on a 4 hectare dam near St. George. This particular cover is the Evap-Cap product which consists of a multi-layered, polyethylene membrane containing buoyancy cells, similar to bubble wrap or existing swimming pool cover products, although the material is much tougher to resist degradation from sunlight. Holes in the plastic allow rainfall to infiltrate below the cover. The top of the material is white to reflect heat whilst the underside is black to restrict light transmission, which reduces algal growth. Other products include plastic films with no inbuilt buoyancy which require separate flotation and securing systems.

Figure 1.6.13 – A floating cover installed on a 4 hectare dam near St George, Qld.

Water quality changes can include reduced dissolved oxygen, and a change in water temperature. Complete covering of a storage can impact on bird and fish life.

Significant difficulties can be encountered with installation on large storages above 5 hectares; therefore this is generally the largest size storage for which these products are suitable as a single cover. However the product can be deployed in sections on large dams and in some cases these covers can be deployed as a series of large rafts covering up to 1ha. The installation method and the procedure used to attach the cover to the embankment are important considerations, as is the structural integrity of the product under windy conditions and fluctuating water levels.

Tests have demonstrated that when well managed, these covers are over 95% effective in reducing evaporation from open storages. However, most of these products have a high capital cost and replacement life varies (typically between 10 and 20 years). The cost effectiveness of these systems suggests that they are likely to be more suited to storages which water in them all year round and/or where the productive return on water use is sufficiently high.

Table 1.6.2 - Advantages and disadvantages of continuous floating covers (Source: DERM (2010), Appraisal to identify and detail technology for improving water use efficiency in irrigation in the Queensland Murray Darling Basin)

Advantages	Disadvantages
Highest average evaporation reduction of evaporation solutions	Dust build-up and the growth of weeds on top of the cover
Lowest variability in performance	High capital and maintenance costs
Easy to determine the likely water saving with a high degree of confidence	Disruption to surface wildlife and change in the environment and water quality beneath the cover
Relatively easy to install	High winds may cause damage and removal of cover
Potentially reduces algal growth	Use of cover limited to storages <5 ha
Potentially improves water quality and reduces salinity.	Capital cost is providing no return during dry periods
Low level of expertise required	
Long lasting (10 – 20 years)	

Modular floating covers

Modular floating covers are another type of physical cover which provides an impermeable barrier between the water surface and each individual module. Individual modules come in a range of sizes up to an area of around 3 m^2. Whilst they do not have the structural challenges of a continuous cover, and installation is generally quite easy, they often cover a slightly smaller portion of the total storage surface due to the small gaps between each module. The evaporation reduction performance will depend on how tightly the modules pack together and will generally be slightly lower than for a continuous plastic floating cover, although modular systems still provide savings of up to 90% when applied to the entire surface.

Modular floating covers can also be deployed to cover only a portion of the storage, for example a borrow pit or low portion that always contains water. Modules can be free floating or connected together to form a larger raft. The actual area covered will depend on the number, shape and size of the module and the storage characteristics. Their flexibility and ease of installation (especially when allowed to float freely) is well suited to deployment on large storages. However, stability under high winds is critical and the impact of high flow periods and wash through spillways needs consideration.

Modules are typically made from a plastic material and usually have a reasonably high capital cost (in excess of \$20/m^2). Repair and replacement of modules is reasonably simple. Existing products include AquaArmour, AquaCap and Raftex. The cost per unit and life of the product will be important in determining the economic viability.

Possible water quality impacts may be similar continuous floating covers, depending on the relative area covered.

Table 1.6.3 - Advantages and disadvantages of modular floating covers (Source: DERM (2010), Appraisal to identify and detail technology for improving water use efficiency in irrigation in the Queensland Murray Darling Basin)

Advantages	Disadvantages
Individual modules can be repaired or replaced	High variability in performance between commercial covers available
Virtually maintenance free	High capital cost
Progressive purchase enables initial cost to be spread out over longer period of time	Disruption to surface wildlife
Lightweight, quick and easy to install	Difficult to cover 100% of storage
Possibly improved water quality through reduced algae	Modular cover may not refloat if left in a muddy storage
Low level of expertise required easy to install and maintain by irrigator	High winds may cause movement and loss of covers, especially on dry storages

Suspended structures

Suspended structures (also see here) usually consist of shadecloth which is suspended above the water surface using a cable structure. The shadecloth reduces solar radiation and wind speed and increases humidity between the structure and the water surface, which all combine to reduce evaporation. The shade cloth can come in a range of UV ratings which describe the amount of UV blocked by the shade cloth.

In general shade structures are not as effective in reducing evaporation as floating covers, with evaporation savings of 70% to 80% demonstrated in trials. However shade structures are a proven technology used for many years in fruit production and there is reduced impact on water quality and aquatic life, although algae growth is typically reduced owing to less light penetration.

Most of these products have high capital and low ongoing/running costs but all have a limited lifetime. The cable system typically has a lifespan of over 30 years with the shadecloth most likely requiring replacement once during this period.

They are more appropriate to small storages given the need to suspend the shade cloth above the water, with the maximum suitable storage size being approximately five hectares. The limiting factor is the ability to construct the cable structure.

Hail shoots or valves can be installed into the cloth to reduce the potential for damage. As shadecloth is porous, it allows rainfall to penetrate readily. This means that wind blown soil does not collect on the surface (it either blows off or falls through) and the growth of weeds or algae on the cover surface is therefore unlikely. Furthermore, dam management has no effect on the shadecloth, as it is not in contact with the water. Therefore the storage can be drained and filled without consideration or monitoring of the cover performance.

Table 1.6.4 - Advantages and disadvantages of suspended shade structures (Source: DERM (2010), Appraisal to identify and detail technology for improving water use efficiency in irrigation in the Queensland Murray Darling Basin)

Advantages	Disadvantages
High evaporation reduction	High capital outlay and maintenance costs
Reduces wave action	Limited applicability
Enables entry of wildlife onto storage	Use of cover limited to storages with a surface span less than 120m (typically <5ha)
Allows access to the storage for maintenance operations	Satisfactory anchoring in some poor soils may be difficult
Possibly improved water quality through reduced algae	Specialist skills and significant engineering design required for footings and high tensile cables
Permeability of cover allows direct rain entry and prevents debris build up	
Existing expertise for installation	

Chemical covers

Chemicals which can be applied to water storages to reduce evaporation have potential as low cost methods for reducing evaporation losses and are likely to be particularly well suited to larger storages. However, chemical methods are generally not as effective at reducing evaporation as physical controls. Water savings have been shown to be highly variable, from less than 5% to up to 40% and are strongly impacted by the chemical type, weather conditions, water quality and application method.

Existing chemical products (also see here) are typically either monolayers or chemical films. Monolayers (for example WaterSavr) form a one molecule thick film (monolayer) on the water surface. Existing monolayers are typically long chain cetyl/stearyl alcohols. Other chemicals which form a film on the water surface (such as Aquatain, a silicone based product) are not true monolayers but may also reduce evaporation.

The main limitation with existing products is their variable performance. New generation monolayer products which hope to provide more predictable performance are currently being developed. The advantages of chemical products are comparatively low upfront capital costs and the fact that the product only need be applied when required. Therefore when there is no water in storage the amount of inactive capital is small.

Monolayer molecules are designed to biodegrade readily to minimise adverse environmental impacts. Therefore frequent, repeat application is necessary (between one and ten days). Recent research has suggested that monolayer products do not adversely affect water quality, although water quality can have a major impact on the durability (lifespan) of the monolayer. Surface film products that are not monolayers (e.g. Aquatain) are likely to have very different environmental performance characteristics which do not appear to have been widely researched.

Application of the monolayer product on small storages may simply be achieved by hand from the bank as the chemical has some self-spreading ability. For larger storages, an intelligent application system is under development which can determine the optimum application strategy depending upon current weather conditions and the presence of product on the surface. A distributed network of applicators can then apply product where required to achieve the most cost effective application strategy. Such a system may also be able to select the best monolayer product to match the water quality characteristics and climate of your water storage.

With the current price of water, chemical covers could provide an economically viable option for large agricultural water storages above ten hectares in size, especially if their performance can be improved. They are particularly suited as a less capital intensive investment option for owners of storages with less reliable water supply. Whilst the chemicals typically only last for between one and ten days, application equipment is likely to last for 20 years.

Table 1.6.5 - Advantages and disadvantages of chemical covers (Source: DERM (2010), Appraisal to identify and detail technology for improving water use efficiency in irrigation in the Queensland Murray Darling Basin)

Advantages	Disadvantages
Low initial setup cost	Low evaporative reduction
Lower risk investment for ephemeral storages	Highly variable performance and uncertainty of water savings
Suitable for storages in dry periods	Monitoring of the presence of cover is difficult
Flexibility and ease in application of cover	Not suitable in windy locations
Can be applied only when needed	Possible environmental and water quality concerns
Biodegradable product should limit potential environmental impact	Biodegradable product means longevity is affected
Can potentially be applied by aircraft	
Suitable for large storages	
Can use automatic applications	

Seepage

Identifying seepage problems

If you have identified a seepage problem by measuring your seepage and evaporation losses, the next step is to identify where the seepage is occurring. Case studies of growers who have identified and addressed seepage problems suggest that seepage usually occurs through discrete pathways such as patches of sand or gravel or prior stream beds (paleochannels). In some cases identification of the problem area can be achieved visually when the storage is empty as there will be evidence of tunnelling or areas displaying soil characteristics or moisture levels inconsistent with the surrounding vicinity.

However, most problems are more difficult to identify, and a number of other methods need to be employed.

Soil Imaging

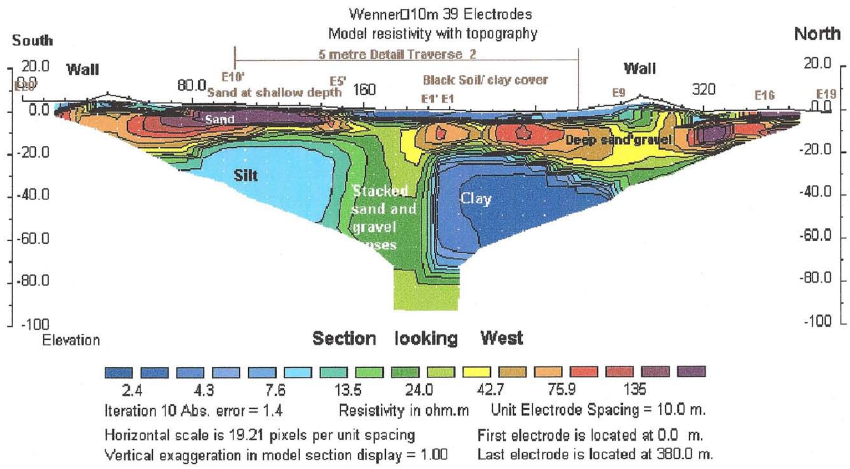
Non-invasive soil imaging techniques such as EM (electromagnetic) surveys (see WATERpak Chapter 2.6) are a cost effective way of looking at the entire storage area. Most of these techniques measure the electrical conductivity (EC) of the material within the sample volume. Electrical conductivity in soil is principally affected by the level of salinity, moisture content and clay content. Therefore, when properly ground truthed to take account of variations in moisture and salinity, these techniques can provide an indication of soil type differences and can be useful aids in identifying areas in which seepage might occur.

EM surveys are the most commonly utilised technique for imaging in agricultural soils and are most frequently conducted using EM31 and EM38 equipment. In typical use, this equipment provides an interpretation of the average bulk soil parameters which provides adequate data for most precision agriculture applications. The commonly used EM equipment provides information to depths of around 1 metre (EM38) and 6 metres (EM31), although a range of alternative EM meters exist with various characteristics and operating depths. Figure 1.6.12 showed an example of a storage EM survey.

More sophisticated techniques and equipment are capable of providing additional information such as multi depth imaging. In this case, the specific characteristics of soil at different depths can be identified, rather than an average of the characteristics over the total depth of measurement. Such techniques might be particularly relevant for identifying storage seepage issues, where specific soil artefacts have been unable to be identified through EM surveys. In particular, the presence of seepage pathways (such as sandy paleochannels) which are otherwise surrounded by clay material can sometimes be difficult to identify using EM surveys alone.

Geoelectric devices (often referred to as DC Resistivity techniques) have been used within the cotton industry more recently, although their use is still confined to a small number of cases at this stage. These devices are capable of providing information on soil at specific depths within the soil profile, and operate across a wide range of depths from less than 2 metres to greater than 40 metres. Some devices can also be adjusted so that the total depth of measurement can be varied. These devices require good electrical contact with the ground or water and have been typically employed in research projects with electrodes hammered into the ground to provide a single transect of information. However it is also possible to tow some devices, which is particularly practical on water surfaces and is therefore particularly relevant for identifying soil characteristics in storages. Figure 1.6.14 provides an example of the type of information that may be produced by such devices.

Figure 1.6.14 – Example resistivity image from an on-farm storage.



Some existing EM surveys have been conducted poorly, although the quality of surveys in general has increased considerably over time as operators have greater experience with the equipment and techniques. Good operators will take into account local conditions that are likely to influence survey results, such as the presence of metal objects. As discussed by David Allen (see Geophysics for the Irrigation Industry):

> *Most EC measuring devices are very strongly affected by metallic objects in their proximity. Shape and grounding of such objects may be very significant. For instance, an ungrounded fence, around a rectangular paddock, with a closed gate may not affect geoelectric devices but may cause problems for electromagnetic devices. Simply by opening the gate, the circuit through the fence may be broken resulting in negligible effect on electromagnetic devices. Similarly, a buried copper pipe may cause problems for a geoelectric device but have less effect on an electromagnetic device.*

In summary:

- Electromagnetic (EM) surveys can provide cost effective mapping of storages and can often identify areas of soil in which seepage is occurring
- EM surveys are not foolproof and may not show specific soil issues in all circumstances
- Alternative techniques such as resistivity imaging can provide additional information including multi-depth analysis of soil characteristics
- Soil imaging complements, but does not substitute, manual investigation. Soil imaging will often need to be ground truthed with sufficient manually collected data and can be used to define specific areas of interest for more detailed manual investigation.

Clay lining

Perhaps the most commonly employed technique to remedy seepage loss is clay lining. Clay lining is useful where there is sufficient suitable clay available near the storage. In nearly all cases, the clay being applied will need to be compacted in order to provide sufficient impermeability. Earthworks can be expensive to apply and it is important to ensure that the works will reduce seepage sufficiently to ensure they are cost effective.

For very small areas where the total cost is reasonably low, the best approach may be to assume that maximum compaction is required. The information below provides some advice on how to apply compaction appropriately.

For larger areas, it will pay to get professional advice from an engineer or soil expert. This advice will tell you:

- Whether the available soil will achieve satisfactory seepage reduction
- The level of compaction required
- The moisture content at which the compaction should be applied
- How the required compaction should be applied

Clay liner design

This section will focus specifically on engineered clay liners, which consist of a layer of compacted clay, typically around 300mm to 1000mm thick. Liner thickness will typically increase with the depth of water to be stored. Correctly designed and constructed clay liners can be very effective at reducing seepage, and although more care is required in their construction, they offer the potential of better performance and may require less earth than ad-hoc remedies. Creating clay liners which successfully alleviate seepage problems requires:

- the correct soil type;
- correct construction techniques, including appropriate compaction at the correct moisture content; and,
- maintenance of the liner to ensure effectiveness over time.

Clay liners are widely used in civil engineering projects which require long term restriction of seepage at extremely low levels. For example clay liners are frequently used to line and cover landfill to prevent contaminated water from escaping. When properly designed, constructed and maintained, clay liners can be extremely effective. However if any of these elements is undertaken poorly, the clay liner may be an ineffective and costly white elephant.

The ideal soils for clay liners should contain 12% to 40% clay and be well graded (universal soil classification Cl, SC or GC). Heavy clays (universal soil classification = CH) which are common in many cotton areas are prone to cracking when dry which reduces the effectiveness of the compaction. However they can be used if protected by a layer of well graded soil to keep them moist (see below). Where the hydraulic conductivity is higher, or insufficient compaction is applied, the thickness of the liner will need to be greater.

The amount of compaction that can be achieved is highly dependent on moisture content. In vertisols, soil strength (and hence compressibility) can vary by two orders of magnitude over the range of moisture contents (for a given density) commonly experienced in agricultural operations (Raper and Kirby, 2006). A standardised laboratory test called the Proctor Test provides an indication of the maximum dry density (MDD) that can be obtained for a given compactive effort and the optimum moisture content (OMC) at which this can be achieved.

Figure 1.6.15 provides an indication of the difference in maximum dry density that can be obtained for a number of Darling Downs soils at different moisture contents. For each soil, it is possible to see that when the soil is too dry, the soil strength prevents the maximum dry density from being achieved. When the soil is too wet, the water takes up too much space in the soil voids and prevents further compression. The maximum dry density and corresponding optimum moisture content for each of these soils is included in Table 1.6.6. The range of optimum moisture contents should be noted and is typical of the range that would be expected within most cotton growing regions.

It should also be noted that the maximum dry density calculated in this manner is related to the testing procedure (in this case standard proctor test). If greater compactive force were applied, a higher MDD would be achievable at a lower OMC. Therefore, it is possible for the field density after compaction to be greater than the MDD determined from this test. The proctor test is widely adopted as a suitable test for determining the amount of compaction required for construction of clay liners.

Figure 1.6.15 - Standard compaction for various darling downs soils (source: FSA Consulting, 2001, Farm Dams for the Sugar Industry)

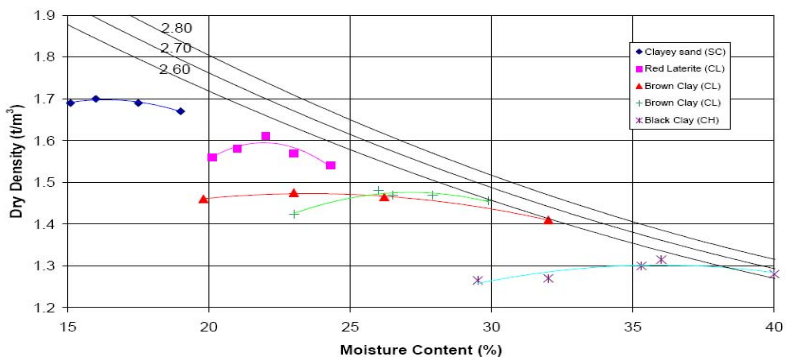


Table 1.6.6 - Optimum moisture content (OMC) and maximum dry density (MDD) for various darling downs soils (source: FSA Consulting, 2001, Farm Dams for the Sugar Industry)

Soil Type	Optimum Mositure Content on a dry basis (%)	Maximum Dry Dentisty (t/m^3)
Clayey Sand (SC)	16.0	1.70
Red Laterite (CL)	22.0	1.61
Brown Clay (CL)	23.0	1.48
Brown Clay (CL)	26.0	1.47
Black Clay (CH)	35.5	1.30

For practical purposes in the field, it is possible to estimate the optimum moisture content by rolling the soil between the hands into a thread four millimetres in diameter (the thickness of a pencil). At the optimum moisture content, this thread will just begin to crumble at this diameter on further rolling.

Applying compaction

There are a number of misconceptions regarding compaction of clay liners. The biggest misconception is the belief that tractors and bulldozers provide significant levels of compaction. This is not true. Table 1.6.7 provides a guide to the average and peak compactive force applied by different types of equipment.

Table 1.6.7 - Average and likely peak ground pressure of a variety of equipment.

Equipment	Average Pressure (kPa)	Possible Peak Pressure (kPa)	Source (average pressure figures)
Bulldozer (D7)	60	240	Ring Tank guidelines
Bulldozer (D11R 710mm track)	160	640	Caterpillar Performance Handbook
Tractor (equivalent to 12 ply tyre @ 150kPa)	180	360	Farm Dams in the Sugar Industry
Tractor (120kW)	250	500	van den Akker and Soane (2005)
Scraper (not specified)	300	600	Farm Dams in the Sugar Industry
Scraper (62 tonnes)	1530	3060	Ring Tank Guidelines
Sheepsfoot Roller	1750		Farm Dams in the Sugar Industry
Sheepsfoot Roller (16 tonnes)	5000		Ring Tank Guidelines
Sheepsfoot Roller	~8000		Pfost et al. (1997) – 40 times greater than rubber tyres.

Most available information provides data on average ground pressure, which is the weight of the machine divided by the total area in contact with the ground. There has been some speculation that this data is misleading, particularly for tracked vehicles which may apply uneven pressure due to the presence of grousers and the number and location of bogies. Recent research has shown that in many cases the peak pressure under a track can be 3 to 5 times higher than the average pressure and 2 times higher for tyred vehicles (Lyasko, 2010). This information has been incorporated into the table above to provide an estimate of the possible peak pressures for each type of machine.

Ground pressure data for bulldozers is usually supplied by manufacturers as they are specifically designed to have a low ground-bearing pressure to improve traction and flotation in soft conditions, thus preventing the machine from sinking. The average ground pressure, even for very large bulldozers such as the Cat D11, is still less than that for tractors, which are operated with low tyre pressures to reduce compaction in fields. Even if the peak pressure is 4 times the average ground pressure, the compaction provided by a bulldozer is at most similar to that provided by a scraper and significantly lower than that provided by a sheepsfoot roller. Note that bulldozers are specifically used to reinstate topsoil to productive condition in mine site reclamation programs because of their ability to minimise compaction.

For storage construction, large scrapers (Cat 631 or larger) are sometimes considered acceptable to provide sufficient compaction when loaded. It should be noted that in all other fields of construction, scrapers are not considered for their compactive effort and thus information regarding their ground pressure is extremely hard to come by.

Sheepsfoot rollers are specifically designed to provide compaction and are ideally suited to compacting clay soils. In addition, they also provide a method of ensuring that each layer of soil (lift) is well bonded to the previous layer. Suitable rollers would typically have an outside diameter not less than one metre nor be more than two metres long. The length of each tamping foot should be at least 175 millimetres from the outside surface of the drum. When fully ballasted, the roller should not weigh less than three tonnes per metre length of drum.

The recommended procedure for providing compaction is as follows:

1. Ensure that all water has been drained from the area of the storage where work is required. Remove any vegetation, sand or silt to expose a firm foundation on which to place the clay lining.
2. Determine the moisture content of the clay to be used for lining. Moisture content can be estimated using the field technique previously described or through soil sampling. If the soil moisture content is less than specified, add water to the soil and mix thoroughly before compacting. Be aware that adding water and mixing soil can significantly increase the cost of earthworks. If the soil moisture content of the material is higher than specified, the material must not be used until the moisture is uniformly lowered to within the specified range, by light ripping, disc ploughing or other methods that assist evaporation and drying.
3. When the moisture content is optimum, place the material in layers, spread evenly and no thicker than 150 millimetres. Each layer should be compacted with a sheepsfoot roller until the dry density exceeds 95 per cent of the maximum dry density as described in AS1289.5.1.1-2003 (or see Table 1.6.6). Normally, six to eight passes of the sheepsfoot roller will be required to achieve the specified compaction. In practice, the compactor should be 'walking on its toes' by this time but still leaving indentations (that is, not a smooth surface). Daniel (1993) provides the following recommendations:

   Heavy, footed compactors with large feet that fully penetrate a loose lift of soil are ideal. Recommended specifications include:

   • Minimum weight: 18000 kg

   • Minimum foot length: 180-200 mm

   • Minimum number of passes: 5

   More passes may sometimes be needed. A pass is defined as one pass of the compactor, not just an axle, over a given area, and the recommended minimum of five passes is for a vehicle with front and rear drums. In the US, the Caterpillar 815B and 825C are examples of equipment in widespread use that have led to satisfactory results in most cases.

Maintaining Compaction

Compacting a surface layer which is subsequently allowed to dry out and crack is not likely to be cost effective, as the effectiveness of the compacted layer will be quickly diminished once cracking occurs. In these situations, a layer of covering material will be required to prevent the compacted layer from drying out. The publication Farm Dams for the Sugar Industry suggests that a 100mm layer of compacted, well graded material can be placed over the top of the clay liner to prevent drying. However for storages which may be dry for long periods of time and therefore may tend to crack significantly, a thicker layer (>300 mm) might be appropriate. It may not be necessary to compact the full layer where thicker layers are employed.

When storages do dry out, it is important to conserve soil moisture to prevent cracking if possible. Regular weed control is very important. Existing storage guidelines recommend against growing crops in any storage, and this is especially so when time and money has been invested in a clay liner. Therefore crops should never be grown in a storage when a clay liner has been applied. Once cracking has occurred, the level of compaction may be reduced upon subsequent swelling, so investment in crack prevention will help to preserve the capital cost of the clay liner construction.

Impact Rolling

Impact rolling is a compaction technique utilising massive non-circular modules. As the module travels across the soil, the non-circular shape causes flat sections of the module to be slammed down onto the soil surface. Self propelled and trailed equipment with drums of between 3 and 5 sides have been used, although the most commonly used technique in cotton growing regions involves a 4 sided trailed drum with a mass of 8 or 12 tonnes (Figure 1.6.16).

Figure 1.6.16 – An example of an impact roller at work (photo courtesy of Broons)

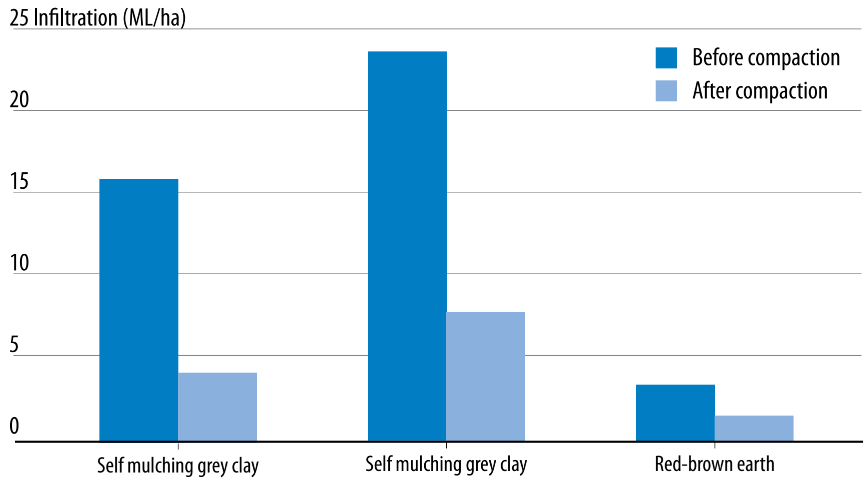
This equipment is seen as attractive for use on reasonably large areas as it has a working speed of around 9 to 12 km/hr and is often used without significant (or any) associated earthworks. The impact roller aims to provide deep compaction (in excess of 300mm) which suggests that it is not necessary to apply compaction to the soil in multiple layers (as in the case for sheepsfoot rollers).

The bearing pressure of an impact roller is not uniform across the area of impact. The corner, for example will provide a static load over a reasonably small area whereas the impact site will provide a dynamic load over a larger area. The dynamic load is still only applied by a portion of the "face" of the roller, not the entire surface. Load cell testing by the manufacturer has suggested that the peak bearing pressure is around 2200kPa. This peak pressure is likely to be applied by an area of less than 20% of the drum surface; however the area of influence will increase with depth in the soil. Multiple passes should provide some uniformity to the compactive effort within the soil.

There is little definitive data regarding the recommended soil moisture for achieving maximum compaction, with various recommended moisture content ranges including: 2% below OMC; 2.5% to 4% below OMC; and up to 7.5% above OMC. Given the impact roller aims to exert compaction at reasonable depths, it would be important to ensure that the moisture content throughout the soil profile is within reasonable limits. Where varying soil moisture exists, it would be reasonable to accept lower soil moisture in the surface layers (0 – 25 cm) in preference to excessively high moisture in lower layers (50 – 75 cm). Impact rollers are not designed to provide compaction in surface layers where the impact and shearing forces can actually reduce compaction.

Research on the use of impact rollers to seal soil in rice fields in southern NSW showed that water infiltration could be significantly reduced if the soil moisture content was greater than about 20% (for these particular soils). The impact roller had virtually no effect when the soil was dry and hard. Infiltration was reduced by 40 to 60 per cent on soils with relatively low initial infiltration rates and was reduced by 70 to 80 per cent on "very leaky" soils (Figure 1.6.17).

Figure 1.6.17 – The effect of impact roller compaction on infiltration in selected soils of Southern NSW (adapted from Reducing recharge from rice fields)



In cotton growing soils, Auzins and Southcott (1999) measured various soil parameters during the use of an 8 tonne impact roller on irrigation channel banks at Lake Tandou in Western NSW. This work showed that:

- Hydraulic conductivity under the middle of the impact roller was reduced to an unmeasurably low value at 0.5 and 0.75 metres below the soil surface following 15 passes of the roller. However the soil structure within the top 0.5m profile was periodically shattered by the roller, thus temporarily increasing the conductivity (for example conductivity at a depth of 0.5 metres initially decreased after 5 passes, then increased after 10 passes before reducing to undetectable levels after 15 passes). Similar patterns of increased hywdraulic conductivity were detected after ten passes in all trials.
- Hydraulic conductivity at the edge of the embankment (outside the roller footprint) actually increased for one trial. It was concluded that the roller encouraged cracks to develop in this area and was attributed to high soil moisture content. This phenomenon may not be a concern on storages where multiple adjacent roller passes occur.
- Cone penetrometer readings suggested that penetration resistance generally increased below around 0.25m in depth. However penetration resistance decreased in the top 100mm, which is consistent with previous research which suggests that the impact and shearing in this zone causes soil loosening.

Avalle (2004) summarises data from three case studies as presented in Tables 1.6.8, 1.6.9 and 1.6.10. It should be noted that these tests may not be scientifically rigorous, and there is no evidence of replication in the trial design.

Table 1.6.8 - Effect of storage floor impact rolling on infiltration using large scale double ring infiltrometer, Clyde Agriculture, Bourke.

Number of passes of impact roller	0	6	12
Infiltration rate (mm/day)	0.30	0.21	0.05

Table 1.6.9 - Effect of channel bank impact rolling on soil density as a percentage of standard compaction, Murrumbidgee Irrigation, NSW.

Percent Compaction	Before Rolling	After Rolling
Surface	91.0%	-
0.5 metres	-	97.5%
1.6 metres	99.0%	99.5%

Table 1.6.10 - Effect of channel bank impact rolling on infiltration at a depth of 100mm using a small scale double ring infiltrometer, Marthaguy Irrigation, NSW.

Number of passes of impact roller	0	5
Infiltration rate (mm/day)	210	No infiltration measurable after 1 hour

Auzins and Southcott (1999) suggest that routine testing should occur during all impact rolling operations. The testing they suggest includes:

- Determine the optimum moisture content (OMC) for the soil at the compaction site.
- Determine the initial soil moisture content at a representative depth (e.g. half the expected depth of compaction) and ensure it is within reasonable limits of the OMC.
- Undertake initial penetration resistance (e.g. cone penetrometers) or in-situ density tests.
- Undertake penetration resistance or in-situ density tests following compaction to provide a quick indication of the effectiveness of the impact roller.

Further case studies of impact roller use are included in the Seepage Remediation Case Studies publication.

Bentonite

Bentonite is a naturally occurring non-toxic clay which is commercially mined and has excellent swelling characteristics. When wet, it expands to 10 to 12 times its dry size. When applied in sufficient volumes, bentonite can form a layer with very low permeability. Bentonite can be applied in three different ways; blanket, mixed blanket and broadcast (sprinkle method). The blanket and mixed blanket techniques are generally more effective, capable of achieving seepage reduction of 65% to 95%. The broadcast method is more likely to achieve seepage reduction of 30% to 50%.

Note that the volumes of bentonite recommended below are often in the order of 100 to 150 tonnes per hectare. Some examples of bentonite application which have been unsuccessful (for example, see Seepage Remediation Case Studies booklet) have occurred at lower rates (30 t/ha or less). The recommended application rate should be understood before committing to, or ruling out, bentonite as an option. Where low application rates are pursued to minimise costs, particularly over large areas, there is significant potential that the application not be sufficient to achieve success. However, when applied correctly, bentonite can be very effective, and is widely used in civil engineering works to prevent water movement.

Blanket/pure blanket

The blanket application method involves placing a layer of pure bentonite on the bottom of the storage. This method usually involves removing at least 150 mm of soil from the area to be treated. A layer of bentonite is spread evenly over the area at a rate of approximately 10 – 15 kg/m^2 (100 to 150 t/ha). The blanket may be compacted to ensure an even thickness and is then covered with the soil that has been removed to protect the bentonite layer from cracking, animals and vegetation.

It is likely that storages in highly cracking soils may need a covering layer of greater than 150 mm thickness to protect the bentonite layer from significant disturbance during cracking. This would be especially relevant for storages which hold water irregularly and are known to dry out considerably. In these cases, a covering layer of over 300 mm might be more appropriate.

Mixed blanket

The mixed blanket method involves incorporating bentonite into a layer of soil. For most soils, around 7 – 15 kg/m^2 (70 to 150 t/ha) of bentonite is required for incorporation into a 150 mm thick soil layer. For best results, the soil should be just moist enough to be worked easily. The soil should be harrowed or disked to approximately 150 mm before the required rate of bentonite is broadcast over the soil. The bentonite and soil layer should be mixed to achieve a uniform layer. The mixed blanket method may be less effective than the blanket method if there is uneven mixing of the bentonite. The incorporation operation should ensure that there are not strips or spots where the bentonite concentration is too low. Once the layer is uniformly mixed it should be compacted with a roller.

Although it is not mandatory, the performance of the mixed blanket method may also be improved by placing a protective soil covering over the bentonite layer. This would be most appropriate for storages in cracking soils that have frequent wet and dry cycles where the bentonite layer and the surrounding soil might be expected to mix over time due to cracking. A protective layer would aim to keep the bentonite layer moist and prevent significant frequent cracking.

Broadcast (sprinkle method)

Broadcast application allows bentonite to be applied to a storage which contains water by sprinkling the bentonite over the water surface. The recommended rate is usually around 10 kg/m^2 (100 t/ha). The bentonite settles to the bottom where it can swell and help to seal the storage floor. This method is not likely to be as successful as the blanket application methods (30 – 50% reduction), and there is little information regarding the longevity of this solution in storages which are regularly emptied.

Effectiveness

The effectiveness of bentonite application has been well researched in the civil engineering field as this product is often used for civil engineering projects. However data from rigorous testing of bentonite in the cotton industry is difficult to find. Trials in Emerald in 2001/02 (see case study at the end of this chapter) showed that the effectiveness of bentonite was possibly compromised when soil cracking occurred.

Bentonite application was also trialled on a number of Darling Downs soils using in-situ ring infiltrometers and laboratory tests in 2005/06. The infield tests involved installing ring infiltrometers into the base of 4 different storages and applying bentonite granules to the ponded water (broadcast method) at a rate of 10 kg/m^2. The results showed a reduction in seepage of between 30% and 50% as indicated in Table 1.6.11. It should be noted that the application was not replicated and the results may not be scientifically rigorous.

Table 1.6.11 – The effect of bentonite application on four Darling Downs storages. Source: Hare (2006).

	Storage 1	Storage 2	Storage 3	Storage 4
Seepage before mm/day	3.29	6.02	58.77	33.37
Seepage after mm/day	2.3	3.17	31.83	19.73
Reduction %	29.9%	47.3%	45.8%	40.9%

Laboratory testing of a bentonite and soil mixture was also conducted on three Darling Downs soils (Campin, 2007). The soil mixture tested was equivalent to a mixed blanket application of 5 kg/m^2 of Bentonite in a 300mm thick layer. The reduction in hydraulic conductivity generally ranged from around 5% to around 60% with an average of 30%. However it should be noted that the ratio of bentonite to soil in this test (5 kg/m^2 in a 300mm soil layer) is lower than the recommended rates for mixed blanket application as outlined above (7 – 15 kg/m^2 in a 150 mm soil layer).

Polyacrylamide (PAM)

Polyacrylamide (PAM) is a chemical belonging to a class of synthetic polymers with long-chain chemical structure and high molecular weight. During production, the length of the polymer can be varied, causing a significant change in its chemical behaviour and functional attributes and making it suitable for a wide range of industrial applications. PAM is believed to have low environmental and public health impacts, requiring little or no regulations over its widespread use.

PAM has been used widely in irrigation, where a small quantity (1 to 2 kg/ha) of food grade quality anionic PAM is typically introduced into the irrigation water to reduce erosion. Erosion reduction is typically due to flocculation that increases settling of sediment within the furrow. PAM has also been found to increase infiltration in medium and fine textured soils (loam to clay) with low organic matter which may be prone to dispersion. In these cases, PAM has acted to stabilise the soil structure, thus reducing surface soil sealing and improving infiltration.

However it has been noted that infiltration may decrease under high PAM concentrations. In Australia this has been noted in laboratory experiments using sandy soil columns and PAM treated water. Within the cotton industry, some growers inadvertently achieved channel sealing when using high PAM dosage rates and interest in PAM for similar applications has increased. Whilst a number of trials have demonstrated some degree of seepage control overseas, there has been little well documented research under local conditions.

It is believed that PAM acts to reduce infiltration by flocculating suspended sediment which settles to the bottom and forms a semi-impervious sediment barrier. It is therefore likely that the effectiveness of this technique will depend on the nature and quantity of suspended sediment. Results from trials of PAM application to canals in the USA have shown immediate seepage reductions from zero (no measurable seepage reduction) to as great as 90 percent. The duration of seepage reduction ranged from one month to as long as five months. However the level of immediate seepage reduction did not necessarily equate to net seepage reduction over an entire irrigation season.

PAM is most often applied in one of three ways:

1. As a solid, directly to the water surface of a body containing water.
2. As a solid, broadcast over the soil surface of an empty storage/channel and subsequently incorporated into the surface layer.
3. As a solution, sprayed onto the soil surface (most typically in channels).

The US NRCS standard for PAM application for canal treatment suggests that the PAM must:

- be anionic
- have a charge density of 10 to 55% by weight
- have a molecular weight of 12 to 24 Mg/mole
- be designated as "water soluble", "linear" or "non cross linked"

As with bentonite and compaction treatments, PAM was trialled on a number of Darling Downs soils using in-situ ring infiltrometers and laboratory tests in 2005/06. The infield tests involved installing ring infiltrometers into the base of 4 different storages and applying PAM to the ponded water at a rate of 60 kg/m^2. The results showed a reduction in seepage of between 30% and 75% as indicated in Table 1.6.12. It should be noted that the application was not replicated and the results may not be scientifically rigorous.

Table 1.6.12 - The effect of PAM application on four Darling Downs storages. Source: Hare (2006).

	Storage 1	Storage 2	Storage 3	Storage 4
Seepage before mm/day	6.72	6.64	58.33	27.51
Seepage after mm/day	3.14	3.05	39.35	6.74
Reduction %	53.3	54	32.5	75.5

Laboratory testing of polyacrylamide was also conducted on three Darling Downs soils (Campin, 2007). A PAM application equivalent to 60 kg/ha was applied as a solution to the soil surface. The reduction in hydraulic conductivity ranged from less than 10% up to 80%, although three quarters of the tests had results of less than 40%.

A 2011 trial of PAM on an entire storage with seepage of 15 mm/day did not provide any significant reduction in seepage, although this trial was not scientifically rigorous (see Seepage Remediation Case Studies p. 14).

Synthetic liners

Many commercial liners of varying strength and durability are available to seal dams including woven polythene, black polythene, vinyl, high density polyethylene (HDPE), butyl rubber, polypropylene and bentonite composites.

The soil that liners are placed upon must be compacted, even and free from sharp objects such as stones and roots that may damage the liner. The underside of the liner must remain vegetation free so the soil is sometimes sprayed with herbicide to prevent any plants growing and penetrating the liner. The liner must be secured, which is often achieved by burying the liner in a trench around the perimeter of the storage.

NSW DPI AgFact AC.24 provides the following information about specific liner materials:

> *Woven polythene, in blue or green, resists tearing but is very susceptible to UV degradation. If it is not protected from sunlight with a layer of soil, it has a very short life. Woven polythene is very unlikely to last 5–7 years in the sun. A grade no steeper than 3:1 must be used to keep the soil from slipping off the liner.*
>
> *Black polythene also has a short life due to UV degradation. It is also quite thin, generally less than 0.4 mm, and is susceptible to puncturing. It must be covered with a layer of soil to prolong its life. There are two grades of black polythene. One uses reprocessed resin and the other uses prime resin. The prime resin liner lasts longer than the reprocessed resin liner. Also, the thicker the liner, the longer it will last, because it is better able to withstand the continual UV degradation of its surface.*
>
> *Vinyl (or PVC) resists tearing and is more flexible than woven polythene. Again this material needs to be covered with a layer of soil to protect it from sunlight.*
>
> *HDPE has a longer life and is tougher than vinyl or woven or black polythene. It resists tearing and does not need to be protected from UV exposure.*
>
> *Butyl rubber is also resistant to sunlight, is flexible and very tough. Both HDPE*

and butyl rubber are more expensive than vinyl and woven or black polythene.

Composite materials contain a thin layer of bentonite sandwiched between polypropylene material. They are not UV sensitive. Because of the bentonite material, small ruptures in the liner are self-healed. However, these liners must be covered with soil to protect them from major punctures.

Western Australian Department of Agriculture Farmnote 5/2003 suggests that the best available membrane lining materials are polypropylene and high-density polyethylene (HDPE) which can both be stabilised to withstand the effects of ultra-violet radiation. When installed to specification, an exposed liner of polypropylene 1 mm thick has a life expectancy of at least 17 years, and an exposed liner of 1.5 mm HDPE has a life of 20 years. However these lifespans only account for UV degradation, not physical damage.

Synthetic liners are more or less impermeable and should provide seepage reduction in excess of 90%. The effectiveness of liners will largely depend on ensuring that they do not become damaged, which is of particular concern for cotton storages which are frequently empty. The liner may be susceptible to damage by animals, vegetation and storms during these periods and options to prevent potential damage will need to be considered. A minimum liner thickness of 2 mm is recommended to help resist physical damage. A soil covering may be most helpful to reduce animal and storm damage although the likelihood of damage by vegetation may increase. Furthermore, a soil covering may increase the difficulty of identification and repair of any areas that do receive damage. Maintaining soil coverage on batters may also be difficult.

Determine the cost effectiveness of solutions

In most situations, one or more of the seepage or evaporation mitigation strategies discussed above could be applied to an individual storage and would be expected to achieve effective water savings. However, investment in one of these strategies must ultimately be made in terms of whether the water can be saved economically. By the time you get to this stage, you should have:

- Measured your seepage and evaporation losses.
- Examined the potential seepage or evaporation mitigation options.
- Selected those that would be most likely to provide effective reduction of seepage and/or evaporation.
- Ensured that these selections are able to be installed on your storage.
- Understood the practical considerations of the particular technique, including the ongoing management and maintenance requirements.

It is now important to determine how economically each method is able to save water. This requires determining the total cost of the particular mitigation option as well as the likely amount of water that will be saved. The Evaporation and Seepage Ready Reckoner is an online tool which enables a basic economic analysis. Depending upon the complexity of your particular situation, it may also be worthwhile engaging a specialist consultant.

Evaporation and seepage ready reckoner

The Evaporation and Seepage Ready Reckoner undertakes two major tasks:

- Firstly, it determines the typical amount of water loss from a storage. To do this, it requires the storage geometry or surface area data and, on a monthly basis, an estimate of how frequently the storage holds water (proportion of years the storage has water in it) and how much water would typically be in the storage.
- Secondly, it uses information about the selected evaporation and/or seepage solution to determine how much water would be saved, to calculate the Net Present Value of the strategy and to determine how cost effective the strategy is in terms of cost per ML of water saved.

To use the ready reckoner, a user is required to enter:

- The storage geometry or surface area data. This information is used to model the actual surface area for a given depth of water. Irregular shapes can be accommodated by simply entering the surface area at the top water level and of the base.
- Monthly evaporation. This information is easily selected using an interactive map.
- An estimate of the amount of water typically in the storage in each month.
- An estimate of the percentage of years that water is in the storage for each month.
- Seepage rate information (if known).

- Data about the evaporation or seepage mitigation system to be evaluated. This typically includes the predicted effectiveness of the solution, the capital costs, expected lifespan and on-going maintenance costs.

The Ready Reckoner can handle a wide range of evaporation or seepage solutions including:

- Split cells
- Increase wall height
- Continuous floating covers
- Modular covers
- Chemical covers
- Suspended covers
- Impermeable liners
- Clay liners
- Bentonite
- Polyacrylamide (PAM)

It is also possible to use both an evaporation and a seepage solution at the same time.

The economic analysis undertaken by the Ready Reckoner involves calculating the net present value (NPV) of the capital and on-going costs associated with the chosen solution. This value is then annualised over the lifespan of the works and this annual cost is compared to the amount of water saved per year.

It should be noted that in practice, the amount of water saved each year will vary depending upon the amount of water in storage and the actual climatic conditions encountered. The Ready Reckoner operates on the basis of a typical water holding pattern, in other words, the average amount of water that a storage would hold over a long period of time. It is therefore important to enter this information correctly.

A recent analysis of cell division and wall height strategies on 15 storages demonstrates how the Ready Reckoner may be used. This publication includes a flowchart which explains the analysis procedure and demonstrates the impact of different water holding patterns on the cost effectiveness of solutions.

Storage maintenance

Prevention is better than a cure! Simple storage maintenance and monitoring can sustain the efficient state of a storage and minimise the long-term costs of seepage mitigation strategies. Detailed information on storage maintenance is included in the Guidelines for Ring Tank Storages. The major steps include:

- Visually inspect storages every one to three hours during filling and every two to four weeks during normal use.
- Take objective measurements (e.g. survey levels, GPS, crest width measurements, etc.) to identify storage changes over time.
- Maintain the crest, as it is typical for crest height to reduce over time due to erosion at up to 25 mm per year.
- Maintain batters by grading and rolling as necessary to prevent the formation of excessive rills, gullies, tunnels or wave erosion.
- Repair larger defects by excavating, replacing with moist soil and compacting. Placing dry soil into large defects is not a long term solution as this soil is easily remobilised and washed out.
- Keep storage batters and crest free of vegetation. Even grass has been found to seek out moisture from deep within storage walls during dry periods, leading to structural failures. Use non-residual herbicides and ensure no trees are placed within 15 metres of the toe of the embankment.
- Maintain the floor and borrow pit to prevent ineffective storage space (dead water). Manage dry storages to conserve soil moisture to prevent cracking and avoid the need for significant water volumes upon re-wetting. Avoid any vegetation.
- Fill storages with caution, especially after a period of prolonged dry weather. The guidelines contain further information about storage filling precautions.

Case study, Dam evaporation and seepage mitigation trial

In 2001, a local Emerald irrigator measured losses of 1 m in less than a month from his newly constructed water storage. Aware that water storages were a source of large water losses on farm, and concerned by the losses he had experienced in his own operation, the irrigator teamed up with Emerald's water use efficiency (WUE) officer and water use efficiency researchers to quantify what was being lost, and what could be done about it.

An on-farm trial was designed to look at accurately measuring losses of evaporation and seepage from on-farm storages and to trial various commercially available tools for reducing seepage and evaporation. Eight 70,000 litre capacity dams were constructed, as listed below in Table 1.6.13.

Table 1.6.13. Trial dams

Dam	Size (m)	Treatment
1	4 × 4 × 4	uncompacted, uncovered (control)
2	2 × 8 × 4	compacted, deep and narrow construction
3	4 × 4 × 4	compacted, lined and covered (Figure 1.6.18)
4	4 × 4 × 4	compacted and top-covered
5	4 × 4 × 4	compacted and lined (Figure 1.6.19)
6	2 × 5 × 6	compacted, shallow and wide construction
7	4 × 4 × 4	treated with bentonite (sides and base)
8	4 × 4 × 4	compacted (base and sides)

Figure 1.6.18 Covered and lined dam. Polypropylene liner and polyethylene cover

Case study continued

Figure 1.6.19 Lined dam

The eight dams were constructed by a private contractor who specialised in building dams. A sheepsfoot roller was used in those treatments that were compacted. Liners and covers were installed by Darling Downs Tarpaulins. In 2001 bentonite was incorporated into dam 7 as a mixed blanket and in 2002 bentonite was broadcast into the dam.

The trial was monitored weekly to measure evaporation and seepage losses. A water reticulation and float valve system was used to top up the trial water levels once a week. A weather station was erected at the site to monitor site conditions. Dams were filled and maintained at the expense of the irrigator himself. Dams 3 (covered and lined), 4 (covered), 5 (lined), and 7 (bentonite) were monitored using ultrasound equipment with the help of Queensland Natural Resources & Mines (NR&M).

Losses from evaporation and seepage that were recorded over a two-year period are shown in Table 1.6.14.

Table 1.6.14. Water storage daily losses (mm) from 2001 to 2003

Treatment	2001/02	2002/03
Covered and lined	4.73	4.55
Covered	10.53	7.44
Lined	6.86	6.18
Bentonite	29.13	55.58

The data for the two seasons show fairly consistent results, with the covered and lined dam retaining the most water, followed by the lined treatment. Water was lost more readily through seepage than through evaporation.

Case study continued

The covers used for this trial were made of a plastic material with air pockets to keep it afloat and holes to allow rain through (E-Vap Cap®). Throughout the two seasons a number of technical problems occurred with the covers. In December 2002 the covers blew off during a storm and during the 2002/03 season silt and algae started to affect the covers' flotation. Further research and improvements are being undertaken by the National Centre for Engineering in Agriculture on these covers and other evaporation-reducing products.

Cost of covers – $6.60/m², 5 year guarantee

The liner used was a 0.5 mm high-density polyethylene sheeting fusion welded to fit the dam. Holes have started to appear in the lining. It is suspected that kangaroos after having a drink may put holes in the lining trying to get out. Holes in the lining started to diminish the effectiveness of the lining, but it is still reducing water losses from the dam (Table 1.6.14).

Cost of liner – from $3.56/m² to $8/m², life expectancy 25-30 years

Bentonite was chosen, as it is a non-toxic, naturally occurring clay chemical compound sodium montmorillonite that swells when wet. This expansion helps to seal pores and cracks in the dams and water channels. Between the 2001 season and the 2002 season the dams were allowed to dry out, allowing cracks to appear. Cracks in naturally lined dams can cause weaknesses, increasing water losses when filled. The bentonite dam lost more water during its second season because of this problem. At the start of the 2002 season, water use efficiency officers broadcast bentonite into the dam. Broadcast is a recommended method of application, but in our trial it was not effective. Basic dam maintenance could have been used to minimise the losses such as maintaining a minimum water level and filling cracks.

Cost of bentonite – $15/40 kg

Mixed blanket – 7 kg/m²

Pure blanket – 10 kg/m²

In the first year of this trial the irrigator incorporated bentonite into the walls of his own on-farm storage in an attempt to reduce seepage. Due to the dam being regularly filled and emptied throughout the year, the irrigator is unable to maintain a minimum water level. Since the incorporation of bentonite, water has continued to be lost through seepage, but the amount of water being lost from the dam was reduced as a result of the bentonite. Water savings from bentonite will vary and for good results it is important that it is applied evenly, compacted and well maintained.

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1.7 Metering

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IRRIGATION AUSTRALIA

Key points

- A water metering solution consists of the meter and installation conditions. A meter is only as accurate if it is installed and maintained correctly.
- There are many different types of meters with different characteristics, accuracy levels and prices.
- A whole farm metering solution might consist of a variety of meters measuring different components of the system.
- Water meters can be used to establish pump efficiencies and benchmark irrigation system performance.
- Installation and maintenance are key for reliable metering and should be considered in any infrastructure development / modification.

The need for metering

The value of measuring volumes of irrigation water has become increasingly important, especially in times when water availability becomes scarce (due to drought, water reform or other reasons) and energy costs increase. In an on-farm context, irrigation water is typically metered for 2 main reasons:

- Measurement for use. This has historically been the most common reason for metering. Metering is used by authorities to monitor individual customer use against entitlement, to find out how much water is being extracted from the system (to improve modelling and management) and to bill customers for water used (see "Legislative requirements" below). As charges for water get higher, users demand more accuracy in measurement.

  Key programs to improve measurement of water resources exist at both the state and federal level, including the NSW Water Extraction Monitoring Policy, the Qld Metering Water Extractions Policy and the National Plan for Water Security and National Water Initiative
- Measurement for farm management. Irrigators are increasingly metering irrigation water to make more informed management decisions. Metering helps them to calculate the efficiency of their system, to identify and minimise water losses such as seepage and evaporation and to make better planning decisions and, ultimately, more profitable farming systems.

There is an increasingly wide range of meters available, but irrespective of which meter is used, it is essential that water meters are:

- Installed correctly
- Well maintained
- Read accurately.

Further information is available in the '[Know the Flow]' manual.

Legislative requirements

In recent years both the NSW and QLD state governments have been framing legislative requirements regarding metering. It is recommended that irrigators refer to the conditions and terms of their licence or approval in order to familiarise themselves with their specific requirements.

Where required for regulatory purposes, meters that were installed before 1 July 2010 must meet standards developed under the National Water Initiative. After that date, new water meters, where required, must be pattern approved (by the meter manufacture or supplier) in accordance with requirements of the National Measurement Institute, and to be installed and operated in accordance with ATS 4747 of Standards Australia.

NSW

Until the national standards developed under the National Water Initiative are fully operational, NSW Office of Water, in conjunction with State Water, has developed the NSW Interim Water Meter Standards which set criteria for the supply and installation of water meters. The Interim Standards as far as possible follow and relate to the national standards. Under the conditions and terms of their licence or approval, water extractors in NSW may be required to have a meter fitted to their extraction works.

Metering requirements may vary from area to area and all licence and approval holders should check their conditions statement to familiarise themselves with their specific requirements. www.water.nsw.gov.au/Water-licensing/Metering/Metering

QLD

The Queensland Government has committed to a national water reform agenda to ensure water resources are properly planned and managed. Accordingly, the Department of Natural Resources and Mines (NR&M) is undertaking a program to install water meters across the state in major groundwater and surface water areas where supplemented water from large dams is not provided. The Water Act 2000 and Water Regulation 2002 provides the department with the necessary administrative arrangements to implement metering.

NR&M is progressively installing meters in catchments where water resource plans and resource operations plans are developed and implemented and in other areas that are under stress or that require closer management. The department's metering program mainly applies to users who draw water directly from streams and declared groundwater areas that are not supplemented by infrastructure such as dams or weirs managed by water service providers.

QLD growers seeking further metering information should contact DERM.

Basic Flow Hydraulics

Flow occurs when there is a difference in pressure or head (height) between the two ends of a pipe or channel. Water will flow from high head to low head (from high pressure to low pressure).

Flow rate increases with pressure or head. The larger the pipe or channel cross-section, the higher the flow rate capacity.

One of the fundamental hydraulic equations that governs the measurement and calculation of flow is:

Q = A x V

Where:

Q is the flow rate, or discharge rate (m^3/s)

A is the cross-sectional area (m^2) and

V is the average velocity of the water (m/s)

You can convert flow rate in m^3/s into the more commonly used terminology as follows:

1 m^3/s = 86.4 ML/day

1 m^3/s = 1000 L/s

To determine the total volume of flow (rather than the flow rate) you simply multiply the flow rate (Q) by the total time over which flow occurs.

Example:

A rectangular section of concrete channel is 1 m across and has water flowing at a depth of 0.5 m. The average velocity of the water is 1.6 m/s.

Area = 1 x 0.5 = 0.5 m^2

Flow rate = 0.5 x 1.6 = 0.8 m^3/s (or 800 L/s)

How much water has flowed through the channel over a period of 36 hours?

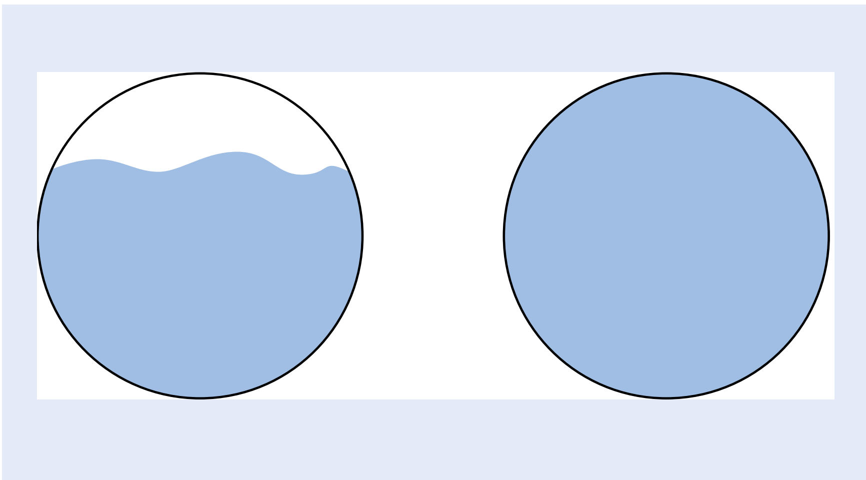
Volume = 800 L/s x 60 (min) x 60 (hour) x 36 = 103 680 000 L = 103.68 ML

Virtually all flow meters use the above equation in order to calculate flow rate. That is, they actually measure the speed of the water and the area of flow and then calculate the flow rate from the equation.

This means that to calculate the rate of flow you need to know:

1. The size of the inside of the pipe or channel dimensions. Larger pipes and channels will allow for a higher flow rate than smaller pipes or channels.
2. The average velocity (speed) of the water. Velocity can be increased by increasing the pressure (head).

Figure 1.7.1. – Partially full pipe on the left is classified as open channel flow. Full pipe on the right is closed conduit flow (Panametrics)



How water flows

Open channel flow - Water in an open channel will only flow if there is a downward slope of the water surface. As mentioned previously, water will flow from high head to low head. The greater the fall, or head, the faster the water will flow.

Closed conduit flow - TThis is commonly known as full pipe flow, but applies to any closed conduit, not just circular pipes. Regardless of the structure, the conduit must be completely full - if water does not completely fill the pipe then the water movement is classified as open channel flow, irrespective of whether or not it is in a fully enclosed conduit (pipe).

Turbulent flow - Turbulent flow occurs when the water swirls in the pipe or channel. This may be caused by obstructions in the flow stream, including the presence of the water meter itself (for example when a mechanical meter is running too fast). Other obstructions can include weeds, incorrectly placed gaskets protruding into the flow, shells, chemical build-up, valves, bends and other fittings.

Established flow - After turbulence distorts the velocity profile it takes a long length of straight pipe before the profile becomes established again. Established flow occurs when the water is flowing through a pipe or channel in a straight line, without turbulence. Most water meters are designed to only measure accurately in established flow conditions.

Most manufacturers recommend a length equivalent to 10 diameters in order to restore established flow conditions, although some people suggest that this distance maybe more like 60 or even 100 diameters. There is also a requirement for straight pipe after the meter location as well, to ensure that any subsequent turbulence does not have an effect on the upstream flow conditions near the meter.

Laminar Flow *– Often the term laminar flow is used to describe the conditions under which metering must occur. In practice, few of the flows that we measure are laminar, but are more accurately described as 'smooth turbulent'. What we require are established flow conditions, so that the velocity profile is regular and predictable.*

Figure 1.7.2. - Velocity profile in horizontal pipe for established flow (Panametrics)

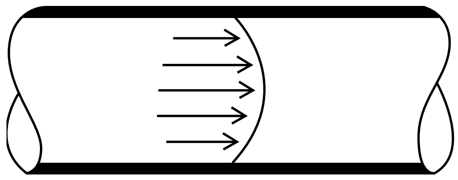


Figure 1.7.3. - Slow streamlines in an elbow and the corresponding velocity profile application A (source: Guide to Flow measurements, Bailey-Fischer & Porter)

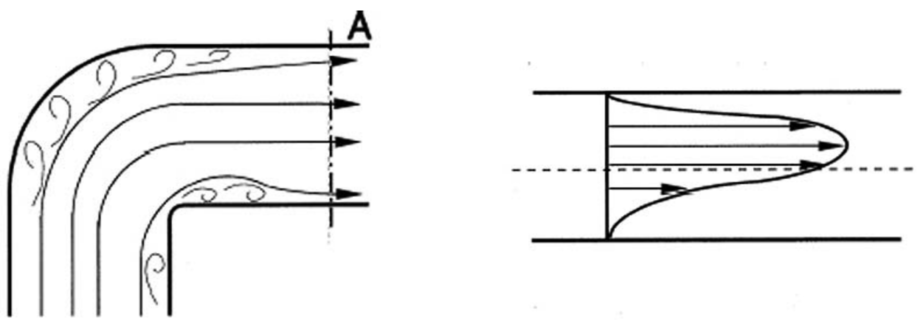
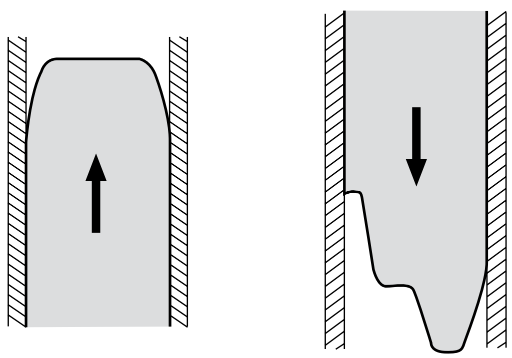


Figure 1.7.4. - Difference in flow profiles in a vertical pipe for upwards flow and downwards flow (Panametrics)



Effects on metering

Because flow meters measure the velocity of the water in order to calculate flow rate, the concepts related to how water flows are important. In particular, it is important to understand how the velocity of water varies across a pipe or channel.

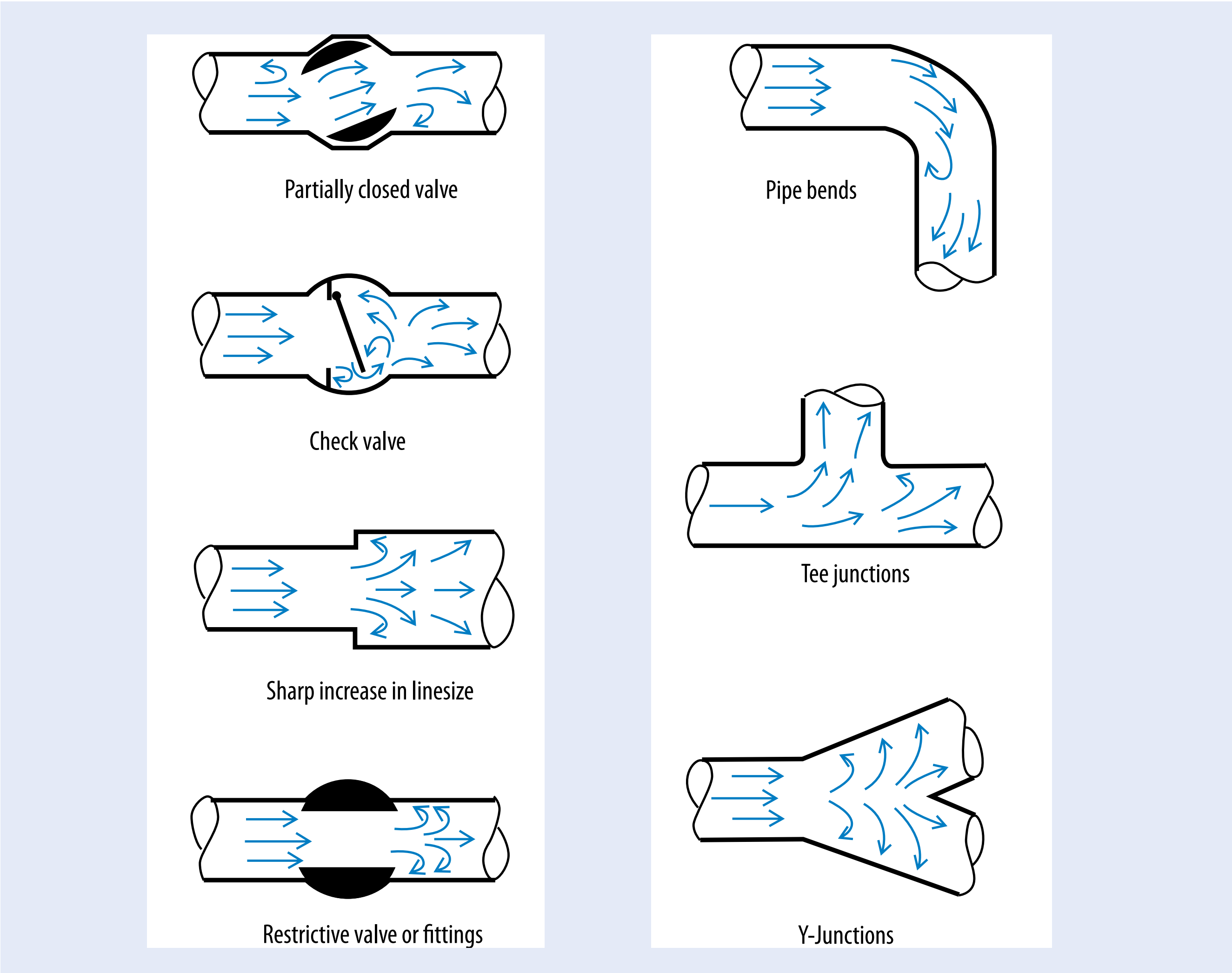
As indicted in Figure 1.7.2, the velocity of water moving a pipe (or channel) is not the same across the entire width of flow. It is fastest in the middle, where there is the least impact from friction with the walls. When flow is established, the velocity profile is very predictable, as illustrated in the figure.

When the flow is not 'established', the velocity profile changes, as indicated in Figure 1.7.3. In this case, following an elbow, the velocity profile is skewed and cannot be correctly interpreted by a flow meter, hence the accuracy of the metering device is affected.

Velocity profiles can be allowed for in the metering calculations if they are consistent. This is achieved when the pipe orientation is anywhere between horizontal and vertical. However, downward flows in pipes have a more uneven profile due to gravity (Figure1.7.4).

For this reason, it would not be wise to try and measure flow in a vertical pipe with water flowing down the pipe. You also must avoid measuring flow in other situations where turbulence is created such as illustrated in Figure 1.7.5. In these situations, the meter should be situated away from the turbulence as indicated by the manufacturer's specifications.

Figure 1.7.5. – Ways that turbulance can develope due to bends, valves and obstructions (Trimec)



Principles of water measurement

There are some key considerations when it comes to measuring water.

Accuracy and Error

Accuracy of measurement relates to the quality of the result. For water meters it is the degree to which a meter conforms to a standard or true value. For example, the accuracy of scales in food stores is tested against known or "Standard" weights. Accuracy is usually discussed in terms of deviation from the standard.

Field conditions can influence the accuracy of a meter. It is important that meters are installed correctly so that, when operating under field conditions, they have an acceptable level of accuracy. The accuracy required usually does not need to be to laboratory standard, for example, you expect greater accuracy for measurement of small amounts of medicine than for bulk water, but incorrect installation may cause too much inaccuracy.

Accuracy is reported in percentages of error, for example, a manufacturer will claim that a meter will be accurate to within ±2%, that is, it can have up to 2% error. This meter is deemed accurate if it reads anywhere between 2% below or 2% above the correct reading.

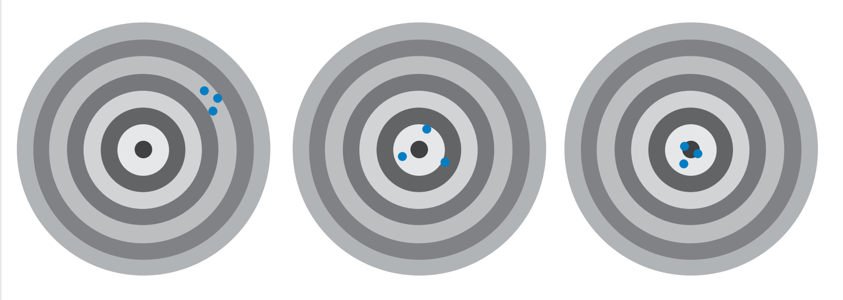
The level of accuracy that is acceptable depends on the situation. Manufacturers test their meters in what is called fully developed flow conditions therefore achieving laminar flow. In these conditions they can claim accuracies of ±2%. Similar accuracies are found when meters are tested in laboratories. In the field, the meters are often operating in a non-perfect environment. Most operators are happy if their meter is operating within 5% in a field situation.

Repeatability

Accuracy is different to repeatability, which relates to the quality of the measuring process. Repeatability is the degree of consistency or uniformity of a result. A measurement can be precise, or repeatable, without being accurate as illustrated in the figure below. In this case, the application of some systematic adjustment (aim lower and further left) would result in better accuracy.

Meters are often precise and then calibrated for accuracy in this way.

Figure 1.7.6. – From left to right, showing repeatability without accuracy, accuracy with a moderate degree of repeatability, and accuracy with high degree of repeatability.



Types of flowmeters

We have discussed that flow rate is directly proportional to the average velocity of the water and the cross-sectional area of the conduit. In turn, the velocity is related to the pressure or head in the system at the point of measurement.

Flow measurement devices do not measure flow directly. Instead, some measure the velocity of the flow and others measure changes in head or pressure. This information is then used to calculate flow. Common types of flowmeters are listed in Table 1.7.1.

We will discuss some of these types of meters that are most applicable to measuring irrigation water.

Table 1.7.1 - Common types of flowmeters

Meters that Measure velocity are:		
Meters	**Subtypes**	**Alternative names**
Mechanical meters	Propeller meters, closed type	Propeller actuated or PA meter
	Propeller meters, open type	
	Paddlewheel meters	
	Turbine meters	Helical rotor
	Positive displacement meters	PD meters
Electromagnetic meters		Magmeters
Ultrasonic meters	Doppler meters	Acoustic meters
	Transit time meters	

Meters that measure pressure or head are:		
Meters	**Subtypes**	**Alternative names**
Venturi meters	Velocity head	
Office meters		
Ultrasonic meters in conjuction with calibrated weirs and flumes		

Figure 1.7.7. – Dethridge meter

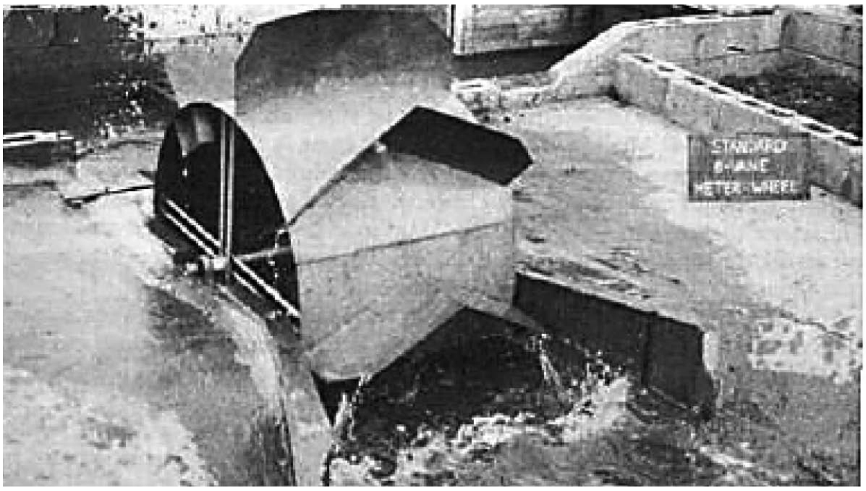


Figure 1.7.8. – Dethridge-Long meter showing the elongated vanes (Sunwater)

Dethridge Meters

Dethridge meters (also known as Dethridge wheels) have been installed in Australian irrigation systems for over 90 years and there are approximately 60,000 still in use today, although in some areas they are being phased out to be replaced by more accurate automated systems.

They are cheap, reasonably accurate and easy to use, leading to their widespread use, particularly for measurement of water supply to farms from regulated schemes

The Dethridge meter consists of a circular drum to which vanes are attached and which revolves in a concrete emplacement. The wheel is turned by water pressure on the vanes and, in turning, displaces a fixed quantity of water between each pair of vanes. A counting device records the number of wheel revolutions and thus a direct measure of the volume of water passing.

The standard Dethridge meter is available in several sizes. Large meters will measure flow ranges between 3.5 to 12 ML/day while small meters measure flow range from 1.5 to 6 ML/day.

Flow rates are easy to estimate in the field as the number of revolutions of the wheel each minute can be counted and multiplied by a factor to get an approximate flow rate in ML/day.

The Dethridge meter was refined during the 1980s and the Dethridge-Long meter was adopted for general use about 1990. It is very similar to the original Dethridge meter but was designed for use when the maximum flow is higher than 12ML/day and/or where there is a large amount of very level land and head losses need to be minimised to maintain good flow conditions and measurement accuracy.

Propeller meter – open flow

The open flow propeller meter consists of a propeller and extended spindle shaft. It is mounted on the downstream end of a pipe culvert with the propeller projecting inside the pipe and its axis located at the centre of, and parallel to, the flow. The culvert pipe must always flow full of water – for accuracy, it must never operate in an 'open channel' condition. The rate of propeller rotation provides a measure of flow rate from which flow volume can be derived and recorded.

There is little head loss through a propeller meter. Installation is critical as the propeller may only sample a small proportion of the flow.

Propeller meter – closed flow

The meter consists of a metal or plastic propeller mounted inside a pipe section with its rotation axis set parallel to the water flow. As water flows past the propeller it causes it to turn. The faster the water is flowing, the faster the propeller spins. This provides a measure of flow velocity from which volumetric flow can be calculated for a given pipe cross section.

Meters are produced in a range of standard sizes with calibrations determined by the manufacturers from laboratory testing.

Closed flow propeller meters are usually configured as an in-line meter in a closed pipe system. It is also used where water is pumped from an open channel or natural water course to irrigate land situated above the level of the water supply. In the latter case the meter is located in the pipework on either the suction or delivery side of the pump. For accuracy, the meter must be carefully located clear of pipe bends or fittings and configured so that the pipe flows full at the meter.

All propeller meters are susceptible to wear and damage because they have moving parts.

Models include (for both open and closed flow):

ABB - R2000
Tempress - Water Specialties
McCrometer - McPropellor

Figure 1.7.9. – Open flowmeter (ABB Metering)

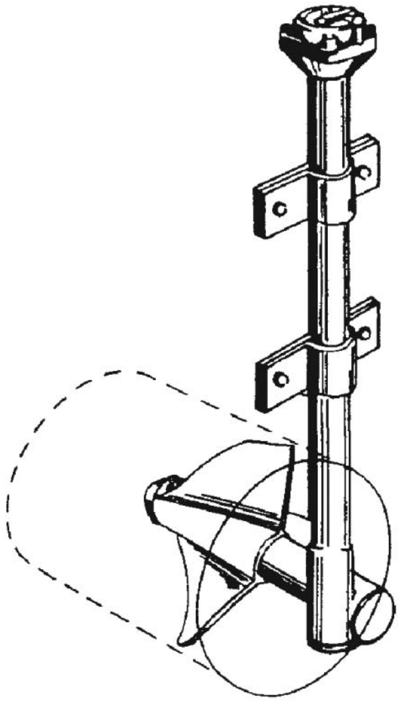


Figure 1.7.10. – ABB R2000 casing and display (ABB Metering)

Paddlewheel Meter

A vertically orientated impeller is rotated by the velocity of water passing through the bore of the meter. Unlike propeller meters, which record velocity in the middle (fastest) portion of the flow, paddlewheel meters often record velocity nearer to the pipe edge. Some versions, which are designed to be used in pipes of various sizes, have an adjustable calibration which must be pre-set for the conditions in which the meter is mounted and tested after assembly in the manufacturers test facility.

These meters are available in various sizes and must be full of water during times of measurement. In pumped systems the meter can be installed in the suction or discharge pipework.

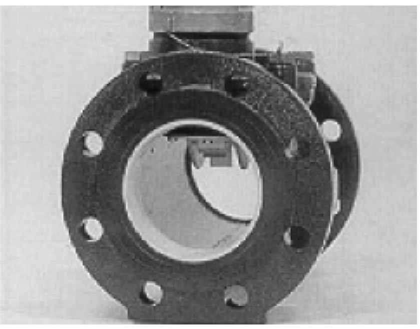
The paddle wheel meter can be used for gravity channel off-takes, pressurised and pumped systems or bore water applications. Due to the large free passage though the meter it is well suited to poor quality water with a high content of impurities and is often used in drainage systems. However some impeller designs have been known to catch debris and drastically reduce accuracy or even stop the meter from turning.

Paddlewheel type meters are also prone to wear and damage as they have moving parts.

Models include:

- Amiad IRT (inline meter)
- Trimec Dual Pulse
- Irrimate Siphon meter

Figure 1.7.11. – Amiad IRT meter, paddlewheel can be seen at the top of the bore



Ultrasonic Meter

Ultrasonic meters (sometimes called acoustic meters) are in widespread use for urban water and wastewater systems and many industrial applications and have found significant use in the irrigation industry in recent years. They operate by producing ultrasonic waves (sound waves) which travel through the water and are either sped up or slowed down by the velocity of the water.

Some meters combine both velocity and depth measurements which allows for measurement in open water surfaces and partially full conduits. Ultrasonic meters use transducers or sensors to measure water velocity in full pipe applications and convert this to flow rate for a particular conduit cross section. Those meters which also measure depth are able to constantly adjust this cross section as water level varies, hence their usefulness in open channel and partially full pipe conditions.

The velocity sensing transducers may be fixed on the outside of the pipe ('non-wetted' types) or may be inserted into the pipe ('wetted' types). Some meters even use multiple transducers to measure velocity in more than one plane, which generally provides greater accuracy.

There are two methods used to calculate the velocity:

Transit Time

This method measures the small variations in time for an ultrasonic sound wave travelling upstream and downstream between fixed points. The velocity of sound pulses in the direction of flow is compared to the velocity of sound pulses opposite to the direction of flow to determine mean velocity and therefore flow rate.

The transducers are often located on or outside the pipe circumference so that there are no obstructions or moving parts to impede the flow. Many of these meters are used only for full pipe flow; however some variants are available that can be used to measure flow in part full pipes or open channels with a free surface. This is more complex and requires additional numbers of transducers and sound paths together with a means of water level measurement.

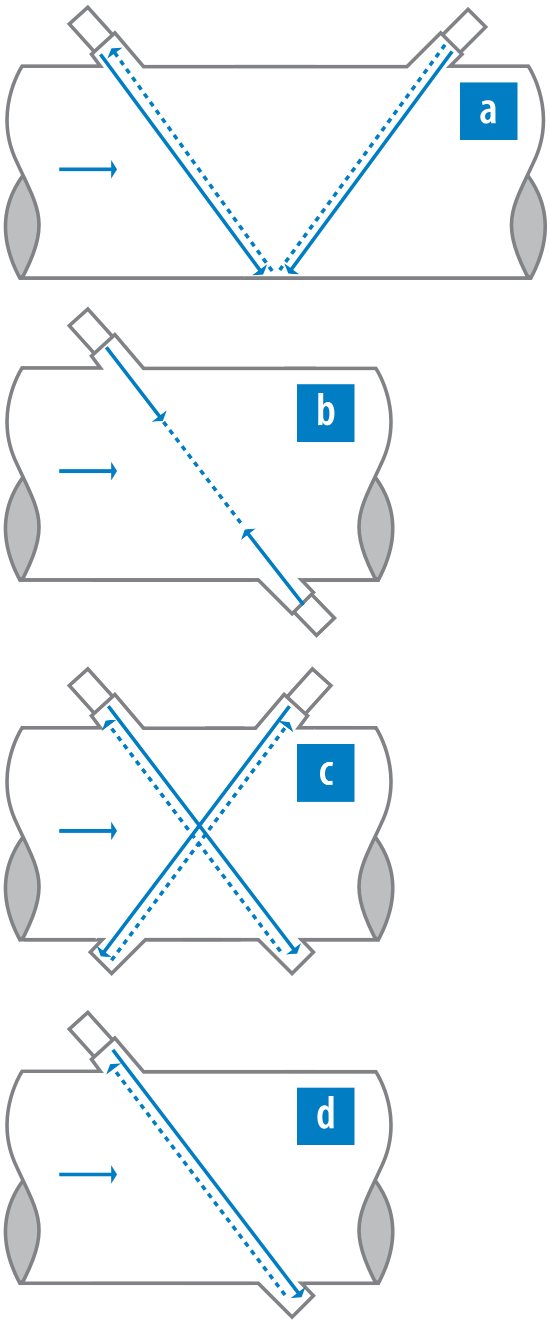
The transducers may be 'wetted' or 'non-wetted'. Non-wetted transducers transmit the acoustic pulses through all or part of the channel's containment structure.

Strap-on, external (non-wetted) meters are quite commonly used for one-off measurements. The thickness of the pipe material must be known or measured for these units.

Models include:

- Panametrics
- Dynasonics

Figure 1.7.12. – Examples of the various ways that transit time sensors may be setup



Doppler

This method calculates the velocity by bouncing sound pulses out into the water mass and reading the pulses that are returned after reflecting from moving particles within the water mass such as air bubbles. This is similar to how radar works.

Meters using the Doppler method generally consist of a sensor that is installed within an existing pipe or structure so the sensor is wetted, although externally mounted units are available. There is no need to install new pipe sections or concrete structures unless there is a need for straight lengths to straighten the flow.

There are various ways to mount the sensors depending on the application. Some may be installed through one inch or two inch 'BSP' fittings welded or clamped onto the external face of the pipe and others by strapping them inside a pipe or structure.

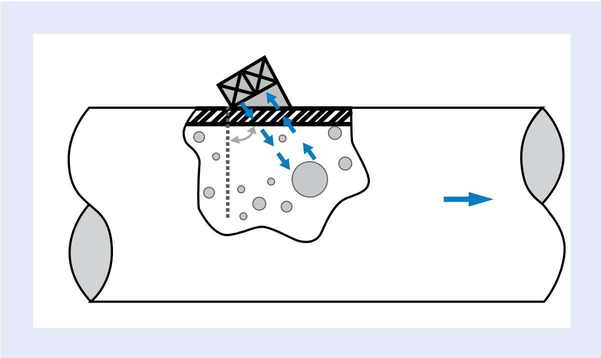
Ultrasonic Doppler meters are capable of measuring flow in full pipe, partial pipe, pumped or gravity fed pipes. In situations where full pipe cannot be achieved, the ultrasonic Doppler meters can have an additional sensor installed to measure the depth of flow. By measuring the depth within a conduit it is possible to then calculate the cross-sectional area and therefore the flow rate. Depth transducers may be ultrasonic, pressure or bubbler type. The most common are pressure transducers due to their high reliability.

Doppler flowmeter performance is highly dependent on physical properties such as the liquid's sonic conductivity, particle density, and flow profile. Likewise, non-uniformity of particle distribution in the pipe cross section results in an incorrect mean velocity. Therefore, the meter accuracy is sensitive to velocity profile variations and to distribution of acoustic reflectors in the measurement section.

Models include:

- Mace Agriflow
- Starflow
- Dynasonics

Figure 1.7.13. - Schematic of a Doppler meter showing the reflected path from a non-wetted transucer. (Mace)



Electromagnetic Meter

An electromagnetic meter consists of a section of pipe with a magnetic field across it and electrodes to detect electrical voltage changes. Under the laws of induction, when a conductive fluid passes along the pipe an electrical voltage is created in the fluid, which is proportional to the fluid velocity.

Electrodes in the probe detect the voltages generated by the flowing water. Measurement of the voltage is then converted to velocity from which the flow rate can be derived for a given pipe section.

This type of meter is produced in a range of standard sizes and flow capacities and comes in two types – insertion and in-line. In-line meters have no parts protruding into the flow and hence are very robust and can easily handle sand, silt and trash. Because of this robustness and very low maintenance requirement, they can be buried and forgotten.

Models include:

- Magflow
- Aquaprobe
- Emflux
- Magmaster
- Dynasonics.

Flumes and Weirs

In Australia, flumes and weirs are commonly used to measure flow in supply channels. A weir is a small holding wall. This can be used for flow measurement by recording the height of the water as it flows over the wall, or through a cut-out in the wall. For example, a v-notch weir is one with a v-shaped notch cut out of the wall and the height of the water is measured as it falls through the notch. A flume is a narrowing of a channel.

Water height can be read with measuring sticks but are now more commonly being measured with ultrasonic meters, which also allow flow to be automatically logged.

Whilst virtually any weir or flume structure can be used to measure flow, the greatest challenge for custom made weirs and flumes is the rating process (calibration). Some configurations have extremely poor precision.

Examples of standard flumes or weirs in use (which are already rated) include Rubicon's 'FlumeGate' system of supply channel control and measurement, and the Irrimate® Flume for measurement of runoff from individual furrows.

Storage Meter

Whilst all the other meters discussed above measure water as it flows past a certain point (in a pipe or channel), it is also possible to measure the change in volume of water within an on-farm storage. Recent developments of automated storage volume meters, have made it much easier to measure and continuously record storage volumes, and then estimate the volume of water that has been moved to other parts of the farm.

There are a few important points to keep in mind:

- The accuracy of the meter is primarily influenced by the accuracy of the known relationship between storage depth and volume – it is recommended that the storage is surveyed to confirm this relationship
- A record of where water is moved to and from at any given time is required if you want to make best use of this data
- The measured volumes do not take account of losses outside of the storage so accuracy declines as you try to apply the data to other parts of the system, the further from the storage, the worse the accuracy.

The most widely available example of an automated type of this meter is the Irrimate™ Storage Meter.

Metering On Farms

Most often, the use of data collected from flow meters on farms is used to inform management decisions. Examples might be to determine how much water is available for use in a season, or to evaluate how well an irrigation system is performing. Hence the location of metering points will determine how the data may be used.

Benchmarking irrigation performance is discussed in another workshop in this series "Benchmarking and Water

Budgeting". Benchmarking may be undertaken on the whole irrigation system (farm scale) or on individual components of the irrigation system (storages, distribution system, fields, individual channels). The location of meters will influence the types of benchmark calculations that can be performed.

Whole Farm

Calculation of performance indices at the whole farm scale requires water inputs from all sources to be accounted for. If all water used on the farm goes through a storage, then a storage meter may be the most effective way of measuring this water volume (although some losses may not be measured, e.g. channel losses from river pump to storage). If not, then all bores, river pumps and other sources must be metered separately. In this situation an on-farm storage will still need to be monitored to account for rainfall capture or on-farm water harvesting

Storage

Storage efficiency can be calculated if you know the volume of water in storage over a period of time and the volume of water used from the storage. This is most easily achieved using a storage meter.

Distribution System

In order to evaluate a distribution system, you need to compare the volume of water entering the system and the volume of water leaving the system. In the simplest form, measurement of a single channel requires a meter at the start of the channel and a meter at the end of a channel (provided there are no outlets in between).

For an entire distribution system, the process becomes much more complex, as all outlets need to be accounted for, theoretically requiring a separate meter for every offtake. It may be easier to use a product like Watertrack for this purpose, or to measure smaller components of the system separately.

The efficiency of distribution systems will vary from season to season depending upon the time that channels contain water, the volume of water transported and the proportion of channels in use.

Ultrasonic Doppler meters with in-built depth sensors are most often used for measuring flows through channels and are best located in culverts or structures where they are not likely to be covered with silt and sediment and the channel cross section can be accurately determined.

Field

In order to calculate basic water use indices for a field, you need to know the amount of water delivered to an individual field. For a furrow irrigated field this can be achieved by measuring the amount of water entering the head ditch. If subsequent fields are also irrigated from the same head ditch, it may also be necessary to measure the amount of water leaving the head ditch to be used on these other fields. Again, an Ultrasonic Doppler meter is most often used for this task.

Another way to perform this measurement would be to measure individual siphons and add the results together. This can be achieved using commercial meters like the Irrimate siphon meter, or by measuring individual siphons with a bucket and stopwatch, or using head-discharge charts. However, results will be strongly influenced by any variation between siphons and the number of siphons measured so it is possible for accuracy to be quite poor. Head ditch losses will not be included.

More detailed evaluation of surface irrigation systems may require measurement of the volume of runoff water. Meters can be installed in taildrain structures to measure bulk runoff volumes, although there are often many technical and installation issues to overcome. A system that includes both furrow flumes to measure runoff and computer simulation to predict runoff as well as detailed calculation of performance indicators, such as the Irrimate™ system, should be seriously considered by anyone wanting to better understand their surface irrigation system.

For drip or overhead systems, any suitable pipe-mounted meter can be appropriately installed in the system. In recent times, overhead systems have had Ultrasonic Doppler insertion meters fitted. Meters installed in drip systems will not be affected by issues with contaminants in the water as they usually have filtration systems installed.

Meter Selection

Selecting the right meter for the job can be a complex process, particularly since many on-farm applications involve difficult conditions for meter siting and accurate operation. There are some key parameters to consider.

Flow conditions

Are you metering in full pipe, open channel or partially full pipe? As discussed, some meters can operate in all three situations whilst others are more restricted in their application.

Nearly all meters require established flow conditions to operate accurately. This means that the installation location must have sufficient straightness and a lack of obstructions to ensure the flow is not turbulent. Manufacturers will specify the length of conduit required to ensure appropriate flow conditions.

Water Source

The source could be a river, surface water, groundwater, open channel or pressurised pipe. The source will have a bearing on water quality with surface water and river water carrying trash and other foreign material while some groundwater can cause iron oxide and iron bacteria buildup on the internal surface of meters and pipes. The source will also have a bearing on the range of flow rates and operating head.

Head

The amount of available head can influence meter selection, particularly for gravity fed open channel systems. Because many metering devices require a certain amount of head in order to operate, this often limits their application in these systems. You also need to take account of how water levels might change over time.

Flow Range

Many meters have an operating flow range over which they can be used. If you operate a meter outside this flow range, then accurate readings cannot be expected. Meters (especially mechanical meters) continually operated at the high end of their flow range may wear out more quickly than meters operated in the middle of their flow range.

Power

Some meters do not need electricity whilst others may have a variety of power source requirements. Many meters that require power can be satisfied by battery/solar systems although there may be some meters which still require mains power. It is important to know what might happen if the power supply is interrupted for some reason – will recording stop? Will existing data be erased?

Accuracy

If there is a requirement for a data accuracy of 2% then it would not be useful to choose a meter that only reads with accuracy of 5%. The reverse may also be true, particularly if it is more expensive to purchase a more accurate meter, when this accuracy is not required.

A manufacturer's claims for meter accuracy are usually well substantiated by laboratory tests supplemented by standardised field tests. However, in practice, a flow meter should be considered as including not only the physical meter but the fully installed system – the data obtained will only be accurate if the metering installation meets all the manufacturers requirements of flow profile, temperature, humidity, flow range, radiation, vibration etc.

Reliability

A meter needs to be reliably accurate so it provides the correct reading time after time

Data Output

There are many different ways that data can be recorded (logged). Some meters include inbuilt data loggers to store the information, whilst others need external data logging capabilities, at additional expense. Some systems may be accessed remotely via telemetry systems.

If you are going to physically download the data yourself, you need to know that there are numerous signal types and methods for connecting to and interrogating the meter. You should have these explained to you and demonstrated so that you are comfortable with the process as some systems are more user-friendly than others.

Accessibility

Some meters may require regular access whilst others could be left alone for years without needing to be seen. Some meters can even be buried and then covered over, which may be useful where the only suitable metering point is underground or where a meter might be vulnerable to damage.

Longevity

The life of the meter will have a direct bearing on the long term economics of a metering decision. On-going maintenance requirements should also be taken into account. Some operating conditions may vary the recommended operating life (for example water quality).

Cost

Cost is often one of the most crucial parameters for meter selection. As mentioned before, the more accurate and reliable the meter, the more expensive it usually is to buy. Additional costs might include installation, maintenance, staff training, data collection, software and lifespan. Don't forget to include the value of the data collected when determining how much you should spend.

Installation

Many key installation issues have already been discussed. These include:

- Nearly all meters require established flow conditions to measure accurately
- Turbulence can be caused by any obstruction including bends, contractions, pumps, valves, etc. and therefore meters should be installed in a straight pipe section away from any of these obstructions.
- Manufacturers should provide recommendations for how much obstruction-free straight pipe or channel is need both upstream and downstream of the meter.
- Many meters require full pipe flow to operate
- In vertical pipe situations, a meter should only be used when the water is moving upwards.
- The accuracy of a metering solution is greatly influenced by the surrounding system

However there are some specific additional points that should be considered for different meter types.

Ultrasonic Doppler Strap-on

Ultrasonic Doppler strap-on meters have become extremely valuable for measurement of open channel gravity systems because they have flexibility in siting and the ability to measure over a wide range of water depths. When setting up a meter for open-channel or partially-full flow, you must program the meter with the channel cross section where it is installed. This is because the meter will automatically measure the water depth and then calculate the cross-sectional area based upon the pre-programmed cross section data.

In most of the applications for these meters, sediment can be a major issue. There are two things you must take into account. Firstly, if the build up of sediment is significant, the cross sectional area of flow will gradually change (reduce) thus influencing the accuracy of the meter. If this is the case, you should investigate redesign of the structure as the hydraulic efficiency of your system will also be suffering.

Secondly, a small build up of sediment is tolerable, provided it does not cover the meter and obstruct the sensing apparatus. To overcome this, you could mount the meter on a raised platform (e.g. a brick or raised bracket) or you could mount the meter so that it is not in the bottom portion of the flow (e.g. mount it partially up one wall of a pipe). You must tell the meter where it is mounted in relation to the water surface so that it can perform calculations correctly.

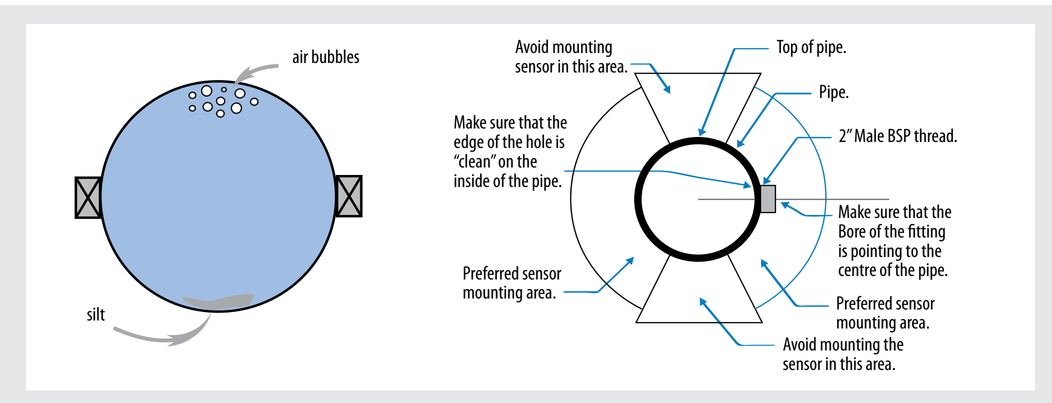


Figure 1.7.14. – Examples of appropriate installations of non-intrusive transit time (left) and insertion Doppler (right) meters.

Ultrasonic Doppler Insertion

Ultrasonic Doppler insertion meters must generally be aligned with the direction of flow so that the signals that they emit are projected at the appropriate angle. Often these meters come with an alignment tool to ensure that they are appropriately aligned to the pipe – make sure that this tool is used during the installation process or an appropriate alignment tool is constructed to ensure this alignment is accurate.

In many cases, the very top and bottom of a pipe are not ideal locations for mounting of an insertion meter, as illustrated in figure 1.7.14. Sediment and air bubbles can congregate in these regions and affect the readings. For transit-time meters (as in the figure) the transducers must directly face each other. For a Doppler insertion meter, the mounting point must be square with the pipe and directly face the very centre of the pipe.

Mechanical Meters – Pipes

When installing mechanical meters in pipelines, all general guidelines need to be considered. They need:

- full pipe
- a straight flow of water with no turbulence
- to be accessible for operation and maintenance.

Most mechanical meters will operate at any angle from horizontal to vertical or oblique. However, they will not be able to read accurately if the activating rotor is not parallel with the sides of the pipe and therefore the straight flow.

Where these types of meters are moved and used in a number of different locations (e.g. the Irrimate siphon meter) you must ensure that the propeller or impeller is accurately aligned with the flow to maintain accuracy.

Whilst the majority of meters need to be installed in a straight section of pipe, the Irrimate siphon meter is typically installed in a slightly curved section of pipe (the siphon). This is because the meter is calibrated in the laboratory in a curved siphon tube of the appropriate diameter.

Mechanical Meters – Open Channel

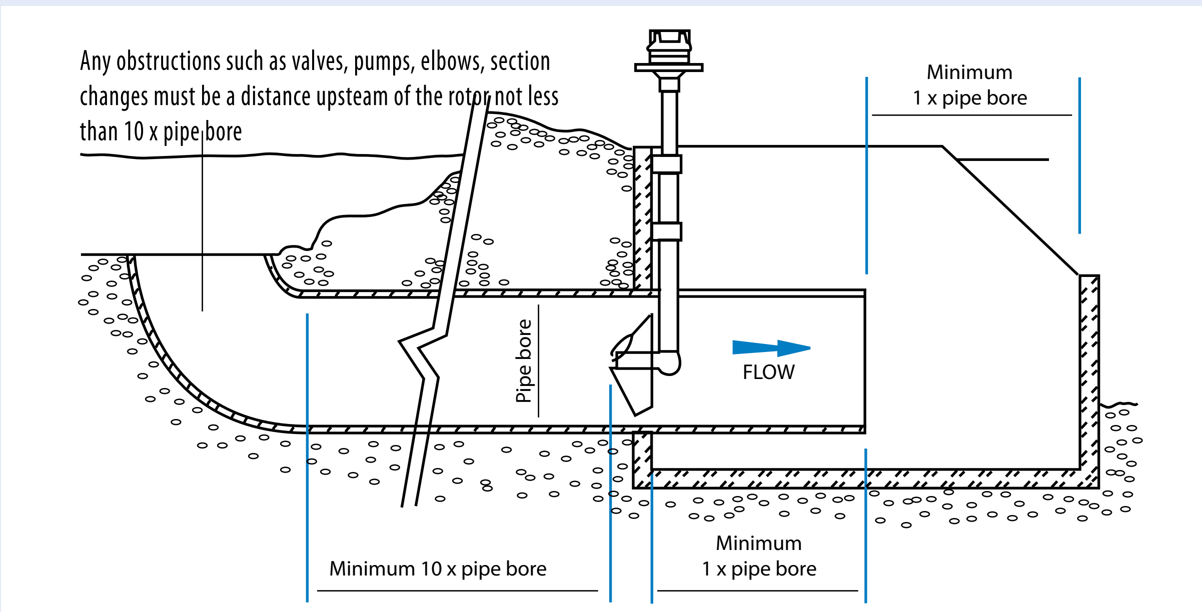
An open channel mechanical propeller meter must be installed within a structure that flows full. This is because these meters do not measure across the whole flow profile and because they cannot determine any change in water depth. Therefore an appropriate structure must be installed or used as per figure 1.7.15. All installation rules already mentioned must be obeyed.

Electromagnetic meters

In-line electromagnetic flowmeters are usually manufactured as a pre-formed pipe section with the detectors and transmitters welded or bolted in place. This makes them extremely simple to install.

These meters have the same requirements for full pipe and straight

Figure 1.7.15. - Example of minimum requirements for straight pipe before and after an open flowmeter installation (ABB Metering).



pipe as all other meters, with 5 to 10 diameters upstream and 3 to 5 diameters downstream the norm.

Reducers can be used for installation in larger size pipelines provided they abide by the rule above so as to ensure laminar flow. Be aware of any hydraulic impact of reducing the size of an existing pipe.

If there is interference or "noise" they may need to be grounded with a ground strap.

Maintenance

Mechanical meters

Mechanical meters, like all things mechanically driven, require maintenance. These meters should be maintained in good condition without wear and correctly adjusted.

It is recommended that these meters are dismantled for cleaning, inspection and routine maintenance every two years. At this time, the complete meter should be removed from the line so that rubbish in the pipe upstream of the propeller may be removed and the meter thoroughly cleaned. Unfortunately this is rarely done in practice, potentially affecting readings.

If wear is too great, the meter should be replaced. In aggressive water (eg. chemically corrosive, high sand content, etc.) it may need fairly frequent replacing or to be made of special material.

Meter failure can be detected by the vigilance of the meter reader or monitoring of readout data to identify faulty meters. Some newer displays have a red flashing light to verify that the propeller is working.

There are two types of meter failure:

- mechanical failure
- environmental failure.

Mechanical failure includes excessive wear of parts such as gears and the complete failure of parts such as broken propeller vanes. This type of failure is usually caused by one of the following:

- flow rates too high
- poor quality parts
- tampering
- fatigue
- vibration

Environmental failure occurs when the mechanism of the meter is fouled or damaged by foreign matter or objects in the water supply system. This type of failure is usually caused by:

- shellfish
- gravel or sand
- weeds
- algae
- iron oxide
- fish or eels
- rubbish eg. sticks.

Errors in meter operation could be caused by:

- changes to the pipeline since meter installation, such as new pumps or valves in the pipe section adjacent to the meter
- air bubbles in the flow
- full-pipe situations not running full due to air entering the system. (Note that this causes meters to record more than the true flow)
- mechanical meters being jammed or slowed by weeds, twigs or fibre in the propeller/rotor/paddle
- build up of iron oxide or iron bacteria or shells on the internal surface of the meter housing or meter pipe
- operating the meter outside it's minimum and maximum flow range.

Ultrasonic Meters

Ultrasonic meters require little maintenance once installed.

Batteries will last several years (5-10 years depending on the frequency of complete discharge). Some meters provide an early warning indicator of low battery power on the LCD readout. Solar panels will need to be cleaned occasionally and inspected for damage.

Internal (wetted) sensors will need to be cleaned occasionally, depending on water quality. However in many sites, they will not require cleaning for several seasons. They may need to be checked periodically to ensure that they are not being fouled or covered with sediment or weeds.

Electromagnetic Meters

Electromagnetic meters also require little maintenance. The straight-through section of pipe has no obstruction to restrict flow, and no moving parts to wear or break. As with the ultrasonic meters, the power source will need to be checked.

Further information

Know the Flow: Flowmetering Training Manual, accessed 1 July 2012.

Baker, Roger C 1989, *An introductory guide to flow measurement*, Mechanical Engineering Publications Limited, London.

Hanson, B and Schwankl, L 1996, 'Error analysis of flowmeter measurements', *Journal of Irrigation and Drainage Engineering*, vol. 124, no. 5, September/October, 1998.

Table 1.7.2. Irrigation guide to flow measurement
– Dethridge meter and electromagnetic flowmeter

	Dethridge meter standard	Electromagnetic flowmeter
Applications		
Open Channel	Yes	Yes
Piped systems	No	Yes
Specifications		
Accuracy (typical)	2%	0.5% to 2%
Flow range	3 to 9 ML/day	Depends on size
Turn-down (flow range)	3 to 1	Up to 1000 to 1
Ideal piping requirement upstream	560 mm	5 diameters
Ideal piping requirement downstream	310 mm	3 diameters
Other special installation requirements	Requires 380 mm level upstream	Requires full pipe
Reliability including tamper-proof protection	Low	Very high
Flow rate indication available	No	Yes
Remote reading capability	Requires separate device	Yes
Output signal type	Requires separate device	Analog & pulse
In-built telemetry output	NA	Yes
Can meter be buried	No	Yes
Average operating life before overhaul	10 years for wheel	20 years
Pressure loss (headloss)	75 mm	Negligible
Resistance to blockage	Low to medium	Very high
Resistance to weed	Medium	High
Relative installed cost	Medium	Medium to high
Power required	No	Yes or solar
Advantages	Easy to use	Highly accurate
	No power	No moving parts
	Robust	No wear
	Low head	Robust
	Reliable	Low pressure loss
Disadvantages	Variable accuracy	Requires power
	Inaccurate at low flows	Requires full pipe
	Affected by varying water levels	Specialist skills to repair
	Wear of bearings and vanes	
	OH&S hazard	
	Restricts access along channel	
	Yabbies cause channel leakage	

Source: ANCID 2000
Please note: The above table is a guide only based on general information and manufacturers' literature where available. You should contact the manufacturer for complete details.

Table 1.7.3. Irrigation guide to flow measurement – mechanical flow meters

	Mechanical Insert (paddle or turbine) meter
Applications	
Open Channel	No
Piped systems	Yes
Specifications	
Accuracy (typical)	2% to 5% of rate
Flow range	Depends on size
Turn-down (flow range)	Size dependent (9 to 1) to (15 to 1)
Ideal piping requirement upstream	10 diameters
Ideal piping requirement downstream	5 diameters
Other special installation requirements	Requires full pipe
Reliability including tamper-proof protection	Medium
Flow rate indication available	No
Remote reading capability	Optional
Output signal type	Pulse
In-built telemetry output	No
Can meter be buried	No
Average operating life before overhaul	4 years depending on water quality
Pressure loss (head loss)	400 mm
Resistance to blockage	Medium
Resistance to weed	Medium
Relative installed cost	Medium
Power required	No
Advantages	Reasonably accurate
	Easy to use
	No power
	Reasonably robust
Disadvantages	Accuracy deteriorates with wear
	Inaccurate at low flows
	Wear of bearings and vanes
	Difficult to detect tampering
	Propeller can be fouled
	Specialist skills to repair

Source: ANCID 2000

Please note: The above table is a guide only based on general information and manufacturers' literature where available. You should contact the manufacturer for complete details.

Table 1.7.4. Irrigation guide to flow measurement – propeller meter and Ultrasonic flowmeter

	Propeller meter Closed type & open flow	**Ultrasonic Flowmeter**
Applications		
Open Channel	Yes	Yes
Piped systems	Yes	Yes
Specifications		
Accuracy (typical)	2% of rate	Better than 2%
Flow range	Depends on size	Based on velocity (0-8 m/s)
Turn-down (flow range)	Size dependent (6 to 1) to (16 to 1)	150 to 1
Ideal piping requirement upstream	5 diameters	6
Ideal piping requirement downstream	1 diameters	2
Other special installation requirements	Requires full pipe	Nil
Reliability including tamper-proof protection	Medium	High
Flow rate indication available	Yes	Yes
Remote reading capability	Optional	Yes
Output signal type	Pulse	Analog & pulse
In-built telemetry output	No	Yes
Can meter be buried	No	Yes
Average operating life before overhaul	4 years depending on water quality	15 years
Pressure loss (head loss)	120 mm	Negligible
Resistance to blockage	Medium	High
Resistance to weed	Low to medium	High
Relative installed cost	Medium	Medium
Power required	No	Yes or solar
Advantages	Reasonably accurate	Highly accurate
	Easy to use	No moving parts
	No power	No wear
	Reasonably robust	Capable of measuring bidirectional flow
		Can be used for a range of pipe diameters
		Negligible pressure loss
Disadvantages	Accuracy deteriorates with wear	Not suitable for filtered water
	Inaccurate at Low Flows	Specialist skills to repair
	Difficult to detect tampering	
	Propeller easily fouled	
	Specialist skills to repair	

Source: ANCID 2000

Please note: The above table is a guide only based on general information and manufacturers' literature where available. You should contact the manufacturer for complete details.

Table 1.7.5. Irrigation guide to flow measurement –weirs and flumes

	Weirs and flumes
Applications	
Open Channel	Yes
Piped systems	No
Specifications	
Accuracy (typical)	5%
Flow range	Depends on size
Turn-down (flow range)	(10 to 1)V notch, (100 to 1) flume
Ideal piping requirement upstream	20 times flow head
Ideal piping requirement downstream	Sufficient for non restricted flow
Other special installation requirements	Sufficient gradient for free flow
Reliability including tamper-proof protection	Low
Flow rate indication available	Requires separate device
Remote reading capability	Requires separate device
Output signal type	Requires separate device
In-built telemetry output	Requires separate device
Can meter be buried	No
Average operating life before overhaul	15 years
Pressure loss (headloss)	Varies 75 mm to 1000 mm
Resistance to blockage	Low to medium
Resistance to weed	Medium
Relative installed cost	Medium to high
Power required	Yes for flow indication
Advantages	Reasonably accurate
	Easy to use
	No power
	Reasonably robust
Disadvantages	Accuracy deteriorates with wear
	Inaccurate at low flows
	Specialist skills to repair
	Requires cleaning

Source: ANCID 2000

Please note: The above table is a guide only based on general information and manufacturers' literature where available. You should contact the manufacturer for complete details.

1.8 Pumps

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Key points

- Pumps are designed to operate within a range of duty points (flow and head)
- Pump curves contain information that is vital for pump selection or evaluation
- It is possible to measure pump characteristics and determine pumping costs
- Pumping costs can be monitored as an indicator of pump wear/failure
- Pump selection is very important – choosing the wrong pump may compromise the operation of the whole irrigation system
- Evaluating pump system efficiency provides information that can significantly reduce operating costs.

Introduction

A poorly performing pump may affect the entire irrigation system, reducing irrigation efficiency and productivity. For example, if a lateral move requires a specific flow rate and pressure but the pump is performing poorly, the flow rate and pressure may not be adequate to operate the sprinklers correctly. The result may be insufficient water applied and uneven distribution, reducing yield and increasing paddock variation.

This chapter contains information about:

- pump types;
- pump duty;
- pump curves;
- pump efficiency and energy use; and
- pump selection.

Common types of irrigation pumps

The main types of pump used for irrigation are:

- Radial flow ('centrifugal') pumps
- Mixed flow pumps
- Turbine pumps.

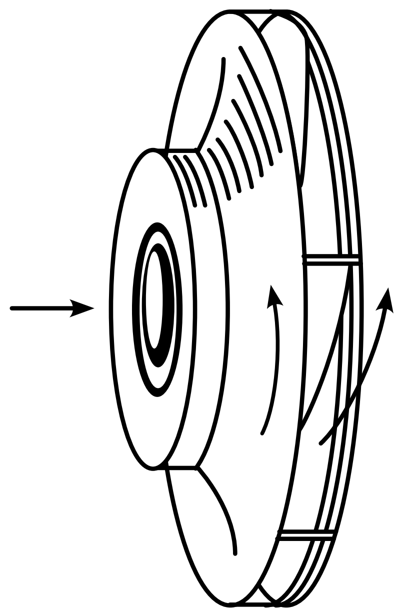
Radial flow ('centrifugal') pumps

Radial flow pumps are commonly referred to as 'centrifugal' pumps. (This may cause confusion, as mixed flow, electro-submersible, most sump and packaged pressure systems are also types of centrifugal pump.)

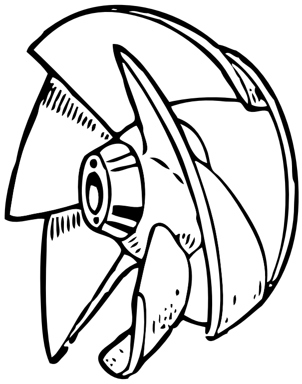
Radial flow impeller – high head – low flow

Liquid enters the impeller axially and is discharged radially. This changes the direction of water by 90 degrees.

The head developed is due to the centrifugal force exerted on the fluid by the impeller.



Mixed flow volute pumps

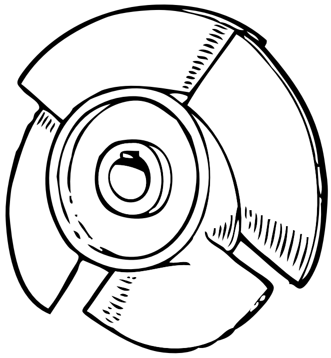


Where large quantities of water have to be pumped against low heads, mixed-flow volute (MFV) pumps are used because it is possible to get higher efficiencies than with radial flow pumps.

Mixed flow impeller – medium head – medium flow

Liquid enters the impeller axially and is discharged both axially and radially. In this case the head developed is the result of a combination of the centrifugal force and the lift produced by the vanes on the liquid.

Turbine pumps



Turbine pumps are mixed-flow and axial flow pumps which direct water to the discharge outlet with diffusion vanes. Turbine pumps are most often used for pumping from bores. Because the bore hole diameter limits the impeller size, the pressure which can be developed at a given speed is also limited. High pressures are achieved by adding extra impellers, called stages, to the pump. These are called multi-stage pumps.

Axial flow impeller – low head – high flow

Liquid enters and leaves the impeller in an axial direction. In this case the head developed is entirely due to the lift produced on the liquid by the vanes.

Variable speed pumping

The popularity of variable speed pumping appears to be growing, largely in response to increasing attention on energy costs. Variable speed pumping is achieved when the speed of a pump is adjusted by a variable speed drive (VSD). Whilst these may be both mechanical and electrical in nature, the most popular type is the electrical variable frequency drive (VFD).

Selection of a variable speed pumping unit may be most appropriate where a pumping system requires capacity to provide for a variation in flow or pressure. For example, where the area of centre pivot irrigation changes due to intermittent end gun operation, or where multiple centre pivots are supplied by a shared mainline. In the past, such situations may have been addressed by selecting a pump capable of meeting the greatest output demand and the use of bypass lines or throttling valves. However this often results in a duty point which consumes unnecessary power.

The selection process for variable speed pumping units is very important, especially as these systems can require additional capital cost. A variable speed pump is not the solution for every situation, and this may be particularly the case where static head is a large component of total head. This is because such systems can have a fairly flat system curve (see below for more information on pump curves) and therefore pump efficiency can reduce quite quickly for only small changes in pump speed.

Furthermore, multi-stage pumping systems, consisting of a combination of constant and variable speed pumps, might provide a more flexible or cost effective solution than a single variable speed pump with the same maximum capacity. An appropriate analysis of pump performance should be undertaken before investment and the use of independent advisors may be beneficial to compare the widest range of possible solutions.

More information on variable speed pumping can be found in resources such as:

Variable Speed Pumping - A guide to successful applications

Variable Speed Driven Pumps - Best Practice Guide

Pump duty

The term 'pump duty' defines the operating conditions of a pump doing a certain job. Pump duty has two components:

the **flow rate**, and

the **head or pressure**

Flow rate

The flow rate is the quantity of water your pump is required to deliver over a specific period of time. It is commonly expressed as **litres per second (L/s)**.

A designed irrigation system should have the flow rate or range of flow rates specified. It is good practice to check your flow rate regularly to determine if your system is still operating as it should. Changes to the flow rate in your irrigation system may be due to wear in the pump, blocked or worn sprinkler components, corrosion in pipes and valves, and changed number or size of outlets.

Accurate measurement of your flow rate is essential. Refer to WATERpak Chapter 1.7 for further information on metering.

Some other flow rate terms:

kilolitres per hour (kL/hr) *or 1,000 litres per hour*

megalitres per hour (ML/hr) *or 1,000,000 litres per hour*

megalitres per day (ML/d) *and*

cumecs (m3/second) *(1 m3 = 1,000 litres)*

Note that some overseas manufacturers use gallons per minute (gpm) - this can be common for centre pivot and lateral move systems. **Be Careful!** Imperial (UK) Gallons and United States Gallons are different!

1 Imperial gallon = 4.55 litres

1 US gallon = 3.79 litres

Head

Head is the term given to the pressure that a needs to be supplied for a specific pumping task. It is often expressed in metres, meaning the pressure at the bottom of an equivalent vertical column of water at sea level.

1m Head – 10kPa – 1.45 psi

1psi – 6.89kPa – 0.69m Head

It is better termed **Total Head (H or TH)** because it is made up of four components added together:

Static Head (SH)

Friction Head (FH)

Pressure Head (PH)

Velocity Head (vh)

Static Head (SH)

The difference in height between the water level and the outlet is called the static head.

This can be broken into two components:

- Suction Head or Lift (SuH) – vertical height difference between the water level and centre line of the pump
- Delivery Head or Lift (DH) – vertical height difference between the centre line of the pump and the water outlet

Friction Head (FH)

Some loss of head occurs in all pipes and fittings in the system due to friction. The amount lost increases with higher flow rates, smaller pipes, pipe length and rougher materials. Smaller pipes may cost less to purchase but they create additional head through increased friction.

For instance:

- *Distributing 400 L/s (35 ML/d) through a 450 mm concrete pipe will result in a friction head loss of 1.1 metres in every 100 metres of pipe length. The same flow through a larger 600 mm pipe results in only 0.25 metres of head in every 100 m of pipe.*
- *675 mm concrete pipe carrying 78 ML per day and lifted 3 m has water velocity around 2.5 m/s. The friction losses from the suction pipe entry and the discharge pipe outlet become significant, perhaps as much as 40% of the Total Head.*
- *200 mm (8 inch) PVC pipe carrying 35 L/s will result in a friction head loss of 0.42 m (4.2 kPa) in every 100 metres of pipe length, whereas a larger size 225 mm (9 inch) pipe will only lose 0.25 m (2.5 kPa) of head in the same length of pipe.*

Pressure Head (PH)

Pressure Head is the pressure required to make an emitter (eg. sprinkler, dripper, etc.) work. It is also known as the operating pressure.

The pressure at or near an outlet is measured by a pressure gauge which should read in kPa. To convert this to metres of head, divide by 10. For instance 300 kPa = 30 m head.

Note: Pressure gauges should be checked to ensure they are reading accurately. Pressure gauges become inaccurate after a few years, or, if attached to a pump, maybe only after a few months.

Velocity head (vh)

This is the kinetic energy, or energy due to motion, in the water at any point.

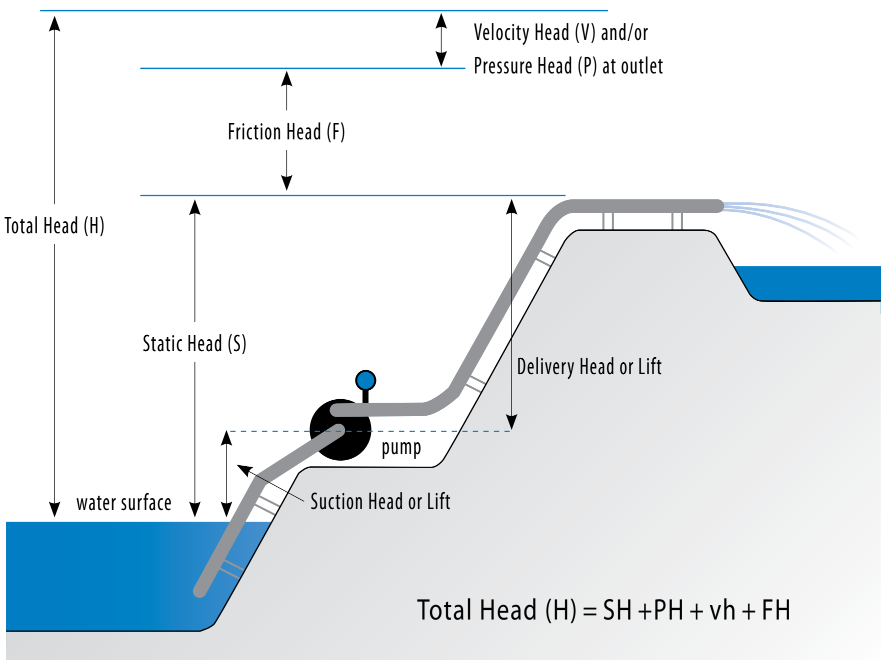
Generally the numeric value of velocity head in a pipeline is quite small compared to Total Head and often disregarded. For example, water flow velocities in pipes up to 3 m/sec give velocity head values of less than 0.5 metres or 5 kPa which maybe only 1–2% of a pressurised system.

When large volumes of water are pumped against a low head (eg. storm water harvesting), Velocity Head in the pipeline may be a significant amount of the Total Head. This results from having no Pressure Head (because the discharge is an unrestricted pipe) and the high kinetic energy of a very large volume of water moving at high speed.

For example, water pumped at 78 ML per day through a 675 mm concrete pipe and lifted 3 m has water moving at around 2.5 m/s. The Velocity Head is 0.32 metres. This is around 11% of the Total Head. The design should evaluate the costs of larger pipe sizes vs operating savings from lower friction and velocity head.

When water leaves a pipeline, say through a sprinkler, Pressure Head is converted to Velocity Head which carries the water into the trajectory or pattern determined by the sprinkler design. This may be significant outside the pipeline but it does not impact on pump selection as Velocity Head was originally part of the nominated Pressure Head.

Figure 1.8.1. Components of Total Head



Example – Total Head

Calculating pumping head in metres

	Example – pressure	Example – surface
Static Head – Suction Lift (river to pump)	3.5 m	0 m (submersed inlet)
Static Head – Delivery Lift (pump to outlet)	5 m	3.0 m
Friction Head	8.5 m	0.1 m
Pressure at outlet in metres (100 kPa = 10 m)	500 kPa ÷ 10 = 50 m	nil
Velocity Head	0.5 m	0.4 m
Irrigator hose losses (if applicable)	100 m × 76 mm poly @ 8 L/s = 12.5 m	n/a
Total Head	3.5 + 5 + 8.5 + 50 + 0.5 + 12.5 = 80 m	3.0 + 0.1 + 0.4 = 3.5 m

For pressurised systems, a simple way to find out the Total Head is by fitting a pressure gauge at or close to the outlet of the pump. The reading here is the combined Pressure Head, Friction Head and Static Head from the pump to the outlet. The Static Head from the pump to the water supply (the Suction or Static Lift) needs to be added to this to give Total Head.

At sea level, the pressure at the bottom of a pipe of water 10 metres high is about 100 kPa (14.5 psi).

Understanding pump curves

Pump manufacturers produce performance charts called pump (characteristic) curves. The main curves show the flow rate at various heads for certain impeller sizes or speeds. The curves for power required and pump efficiency are overlaid on the same axes for convenience. For computer selection of pumps, these curves are built into the computer software.

Flow v head curves

Figure 1.8.2 shows the curves for a particular pump at a set speed but with different impeller size options.

Figure 1.8.2. Pump curves for different impeller diameter at one speed.

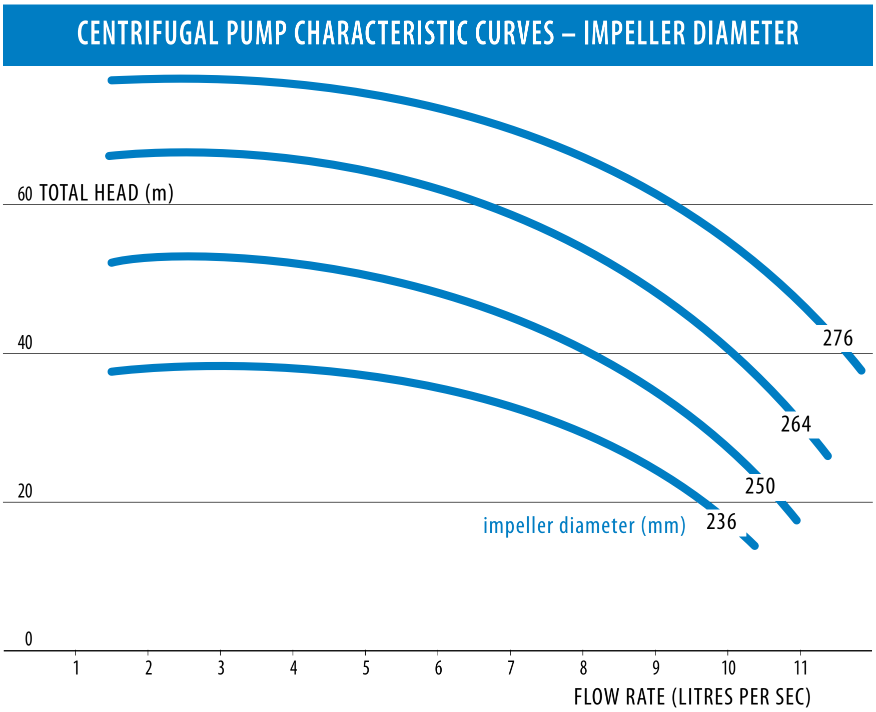
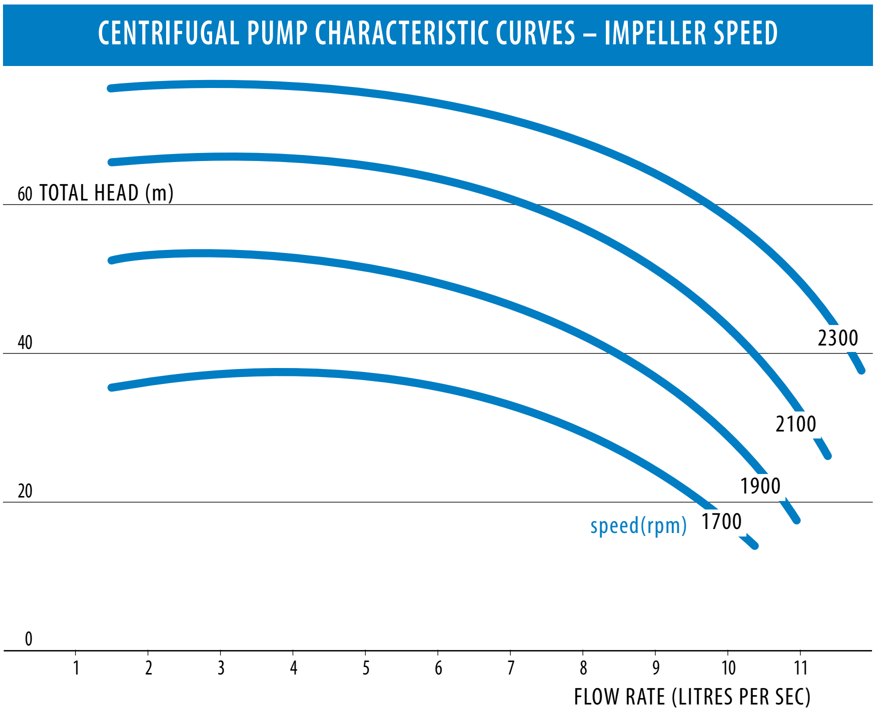


Figure 1.8.3 shows curves for the same pump with one particular impeller size at several different operating speeds.

Using either of these examples, the pump is capable of pumping at rates varying from about 2 L/s to about 10 L/s at a head varying from 15 metres to about 70 metres.

Larger pump examples are included later (Figures 1.8.7 & 1.8.8).

Figure 1.8.3. Pump curves for one impeller at different operating speeds.

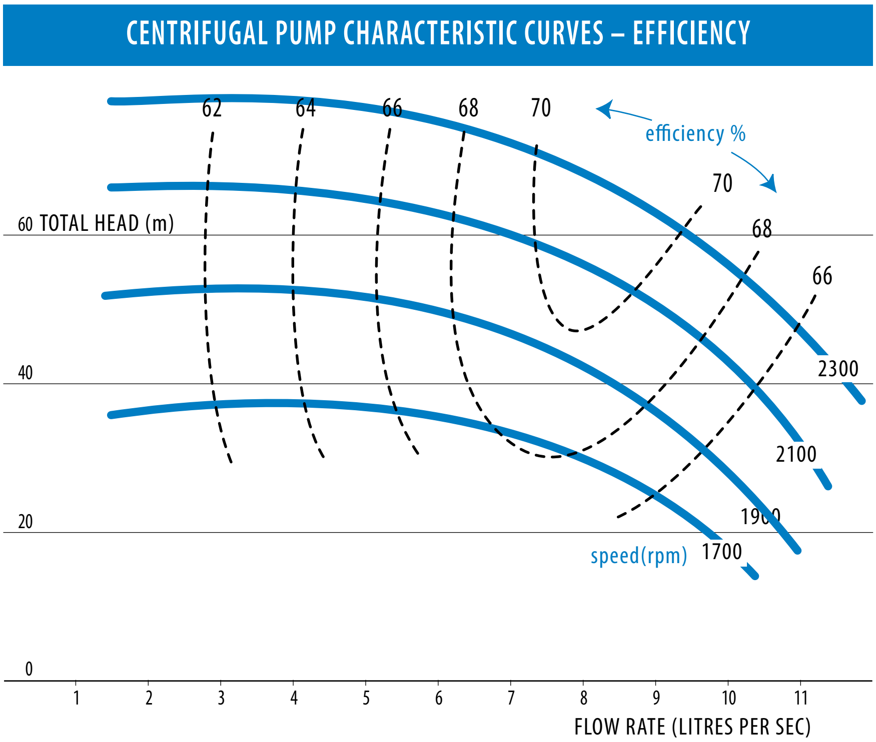


Efficiency curves

The operating efficiency of the pump at each duty point is also marked on the pump curves. They are usually marked with percentages. They show how efficiently the input power (from the engine or motor) is transmitted into energy to pump the water at a particular duty point. This is the pumping efficiency. Like most mechanical devices, it is not possible to achieve 100% efficiency, primarily due to friction.

It is best to select and operate a pump near its peak efficiency. This results in more efficient use of electricity or diesel and thus reduced operating costs. Note that efficiency decreases if the flow rate is too high or too low and if the head is too high or too low.

Figure 1.8.4. Efficiency curves overlaid on Flow v Head curves

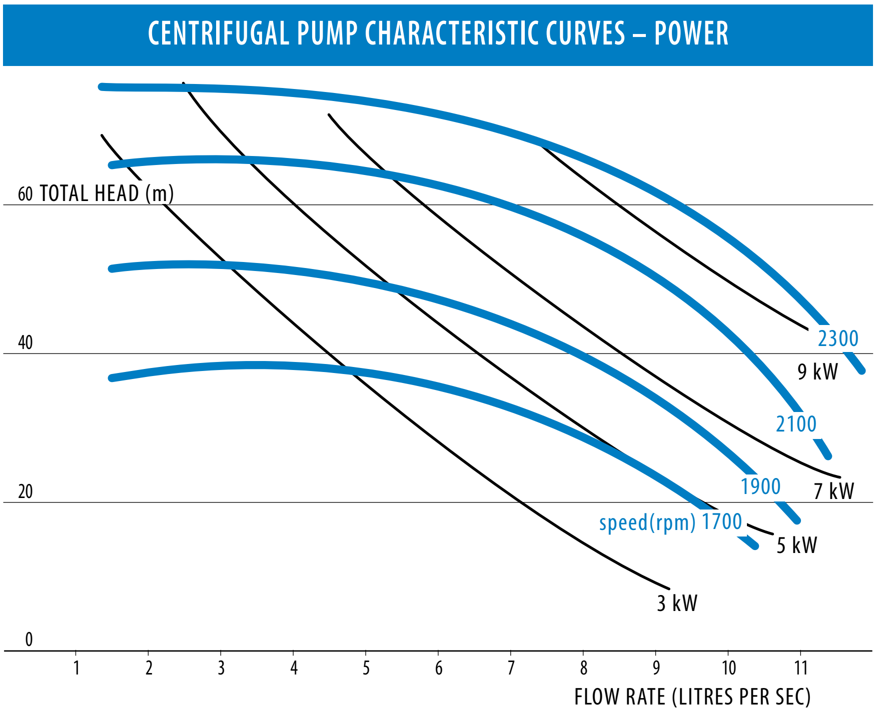


Power curves

The amount of power required to drive the pump (at the pump shaft) is also shown across the other curves (Figures 1.8.5 & 1.8.6) or separately (as in Figure 1.8.8). The power curve is usually marked in kW (kilowatts). You can work out the power at any point by estimating the figure from the closest power curve.

NB. This is the NET power required. Typically the prime mover needs to be 20% more for an electric motor, and 40% more for an internal combustion engine.

Figure 1.8.5. Power curves overlaid on Flow v Head curve



NPSHR

Pump curves supplied by manufacturers often show a separate curve that gives the "Net Positive Suction Head Required" (NPSHR). An example is in Figure 1.8.6. This is the ability of the pump to suck water from the supply source (eg. creek) without causing cavitation of the pump. (Some manufacturers, eg. Macquarrie, use the term Hs for NPSHR.)

Turbine pumps are usually fully submerged, including the pump inlet. This means there is no suction lift. Care needs to be taken that the inlet is submerged according to the supplier's specifications to avoid vortexing and sucking air.

NPSH is discussed in more detail in the pump selection section.

Figure 1.8.6. Complete centrifugal pump curve

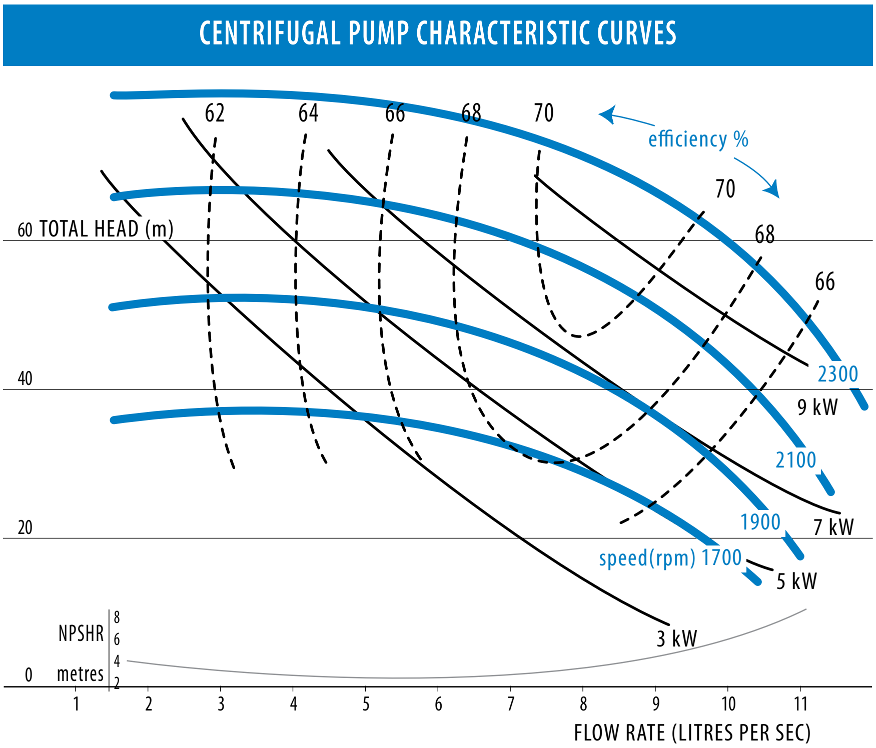


Figure 1.8.7. Example of curves for a mixed flow pump

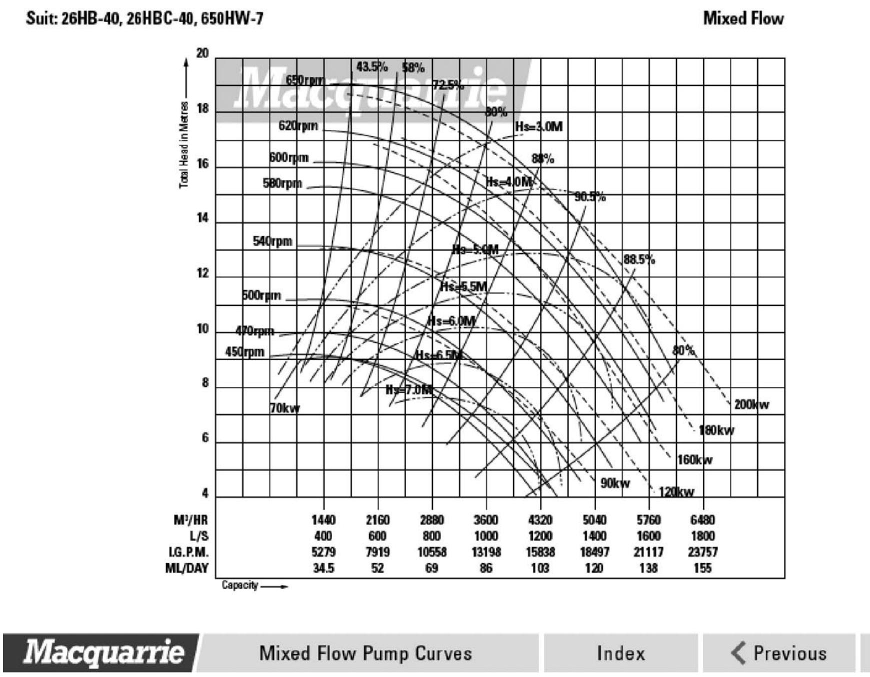


Figure 1.8.8. Example curves for a radial flow pump.

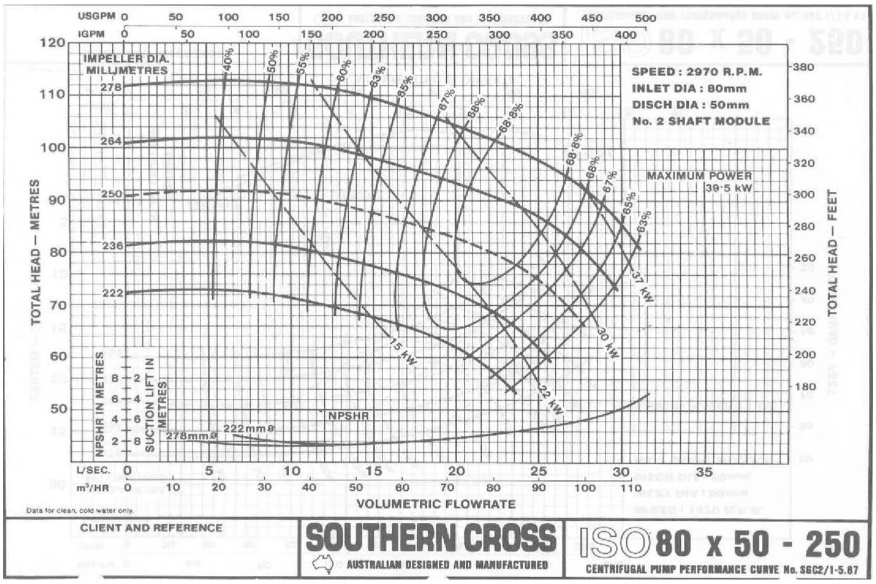


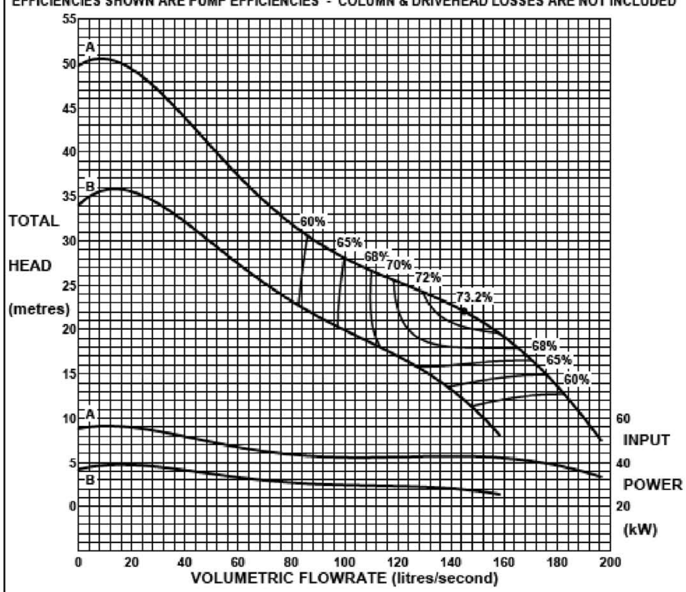
Chart 1.8.9. Example of curves for a turbine pump.

CHANGE EFFIC. AS FOLLOWS	NO. OF POINTS	NO. OF STAGES
LOWER	2	1
LOWER	1	2
LOWER	0	3
LOWER	0	0
LOWER 2 PTS FOR PLAIN BOWL		

VERTICAL PUMPS TURBINE

PUMP MODEL 250FHH	CURVE NO. E10441
2980 R.P.M.	DATE Apr-2001
BOWL DIA. 245 mm	
STANDARD CURVE ILLUSTRATES SINGLE STAGE PERFORMANCE ONLY	K 20.7

EFFICIENCIES SHOWN ARE PUMP EFFICIENCIES - COLUMN & DRIVEHEAD LOSSES ARE NOT INCLUDED



DATA FOR CLEAN COLD WATER ONLY

PUMP PERFORMANCE TO AS2417 Pt 2 Class C

IMPELLER				BOWL			
IMPELLER TRIM A	=	203	mm	PUMP LENGTH	=	685	mm
IMPELLER TRIM B	=	190	mm	ADDITIONAL STAGES	=	222	mm
				MAX. NO. OF STAGES	=	20	
EFFECTIVE EYE AREA	=	191.6	cm²	MAX. PRESS. HEAD	=	685	m
NUMBER OF VANES	=	7		LATERAL STD	=	9.5 mm	MAX 15.2 mm
WR² PER IMPELLER	=	.0354	kg.m²	SUCTION SIZE	=	200	mm
MAX. SPHERE SIZE	=	31	mm	DISCHARGE SIZE	=	150/200/250 mm	
WEIGHT	=	8	kg	DISCHARGE CASE DIA.	=	249/249/296 mm	

tyco Flow Control / Everflow Pumps

46 WILLIAMSON ROAD
INGLEBURN, N.S.W. 2565

Pump efficiency and power requirements

For most irrigators, energy costs and energy efficiency are of major concern due to recent increases in energy costs and uncertainty regarding likely future increases. Pumping constitutes a major component of the total energy costs for most irrigation enterprises; for example the National Centre for Engineering in Agriculture found irrigation was typically between 40% and 60% of the total energy costs on irrigated cotton farms (NCEA - Energy in Cotton). Therefore improvements in pump efficiency can contribute to significant reductions in production costs.

From the pump charts, the theoretical pump efficiency can be determined. This section outlines how to calculate the **actual** pump efficiency. This value may be lower because:

- the wrong pump was chosen for the job
- the pump is worn and needs repair
- it is performing a duty different to the original design

If a pump is not working to maximum efficiency it will cost more than it should to operate. The pump duty and the energy being consumed should be shown on design plans, with this you can benchmark your pump's operating costs and efficiency over time. This indicates if it is still operating satisfactorily.

Pump efficiency of 70 to 85% should be achievable in most circumstances. An acceptable minimum is 65%.

Determining pump efficiency and operating costs

To find out if your pump is performing appropriately, a three step process is needed:

1. determine the theoretical efficiency and power requirement
2. determine the actual efficiency and power requirement, and
3. compare the difference.

Calculation of Pump Power requirement is achieved using the following equation:

$$P = Q \times H \div Pe$$

Where: P = Power (kW), Q = Flow Rate (L/s), H = Head (m) and Pe = Pump Efficiency (%)

or

$$P = (Q \times H) \div (Pe \times 100)$$

Where: P = Power (kW), Q = Flow Rate (L/s), H = Head (m) and Pe = Pump Efficiency (decimal)

Step 1 – Determining theoretical pump efficiency and power requirement:

The theoretical pump efficiency and power requirement can be read directly from the pump chart. Alternatively, it can be calculated as follows:

- Flow rate (Q)
  = 93 ML/d (1076 L/s)
- Total head (H)
  = 7 m
- Efficiency from the pump curve (Pe)
  For pump '26HBC-40' (Chart 1.8.6) = 89% (or 0.89)
- Theoretical Power required at the pump for this 'duty' and efficiency.
  $= Q \times H \div Pe = 1076 \times 7 \div 89 = 85$ kW

Step 2 – Determining actual pump efficiency and power requirement

To determine what is actually happening to an installed pump, we need to take some initial measurements. The power equation above contains 4 parts:

- **Flow rate** – we can measure this
- **Head** – we can measure this
- **Power** – we can determine this by measuring energy (electricity or fuel) usage
- **Pump Efficiency** – this is what we need to calculate

By rearranging the power equation above:

$$Pe = Q \times H \div P$$

Measuring flow and head can be performed quite accurately. But measuring the energy used by the motor driving the pump includes inefficiencies in the motor and drivetrain as well as the pump. In order to calculate pump efficiency correctly, energy losses due to the motor, transmission, climatic conditions, etc. are accounted for through a process called **de-rating**. The tables on the following page provide the information needed to do this.

Table 1.8.1. Motor Efficiency (Me) – electric motors

Power – Approx. motor efficiency
Below 5 kW – 82% (0.82)
5 to 15 kW – 85% (0.85)
15 to 50 kW – 88% (0.88)
50 to 100 kW – 90% (0.90)

Submersible motors lose about 4% more than air-cooled electric motors (eg. where **Me** is 88% for an air-cooled motor it would be 84% for a submersible). Voltage losses through long electrical cables may also be significant. This should be checked with an electrical engineer.

Table 1.8.2. Altitude losses (Dr) – internal combustion engines

m above Sea level	100%, 1.00
200	99% (0.99)
400	98% (0.98)
600	97% (0.97)
800	96% (0.96)
1000	95% (0.95)

100% at sea level means no reduction of power due to altitude – this is 100% of the potential efficiency, not that the engine is 100% efficient.

The altitudes of some irrigation regions are:

Emerald Qld	189 m
Dalby Qld	344 m
Moree NSW	212 m
Gunnedah NSW	264 m
Dubbo NSW	260 m
Hillston NSW	122 m
Wagga Wagga NSW	147 m
Griffith NSW	134 m
Tatura Vic	114 m
Mudgee NSW	454 m

For example, a diesel engine located at Moree, NSW, will produce 99% of its stated power rating. This is expressed as a decimal, 0.99, for our calculations.

Table 1.8.3. Temperature losses – internal combustion engines (Dt)

Air Temperature °C	Naturally Aspirated Engine, % loss	Dt	Exhaust Gas Turbocharged Engine, % loss	Dt
20	0	0	0	0
25	1.8	0.982	2.8	0.972
30	3.6	0.964	5.6	0.944
35	5.6	0.944	8.0	0.92
40	7.2	0.928	10.8	0.892

For example, at 30oC a naturally aspirated engine will have a power loss of 3.6% ie. it produces only 96.4% of the power compared to 20oC. This means the temperature factor (Dt) is 0.964.

Turbocharged engines are typically already more efficient than naturally aspirated, so although the percentage loss due to air temperature is greater, the engine efficiency may still be higher.

Table 1.8.4. Transmission or Drive Losses (Df)

This table assumes the transmission is in good condition and set up properly ie. V-belts in good condition and tensioned, gear drive maintained, etc.

Transmission Type	Energy transmitted %	Df
V-belt drives	90	0.9
Gear drives	95	0.95
Direct drive	100	1.0

For example, a 100 kW motor connected by vee belts will only transfer 90 kW to the pump.

Standard speeds for electric motors are 1450 rpm and 2800 rpm. If the operating speed of the pump is the same as these, direct drive is usually employed. If it is different, a transmission will be needed to gear the speed up or down.

Step 2.1 – Determining energy usage – electric motors

It is important to understand the difference between energy and power. Power is the rate at which energy is used. When measuring electricity, power is usually specified in kilowatts (kW) and energy in kilowatt-hours (kWh).

power (kW) = energy (kWh) ÷ time (h)

Table 1.8.5. Reading electricity meters

	Example
First reading (**R1**)	7517.29 kWh
Second reading (**R2**)	7518.80 kWh
Multiplier (**M**) For this example we will use a multiplier of 40 (often found only on the power bill)	40
Difference between readings (**C**) (energy used during test time)	$R2 - R1 = 7518.80 - 7517.29 = 1.51$ kWh
Total Energy Used (kWh) (**E**) (use the multiplier to obtain the actual energy use)	$C \times M = 1.51 \times 40 = 60.4$ kWh
Time between readings in hours (**T**)	30 minutes = 0.5 hours
Power supplied (kW) (**Ps**) (this is the power supplied to the motor)	$C \div T = 60.4 \div 0.5 = 120.8$ kW

Power supply figures may also be used to indicate if the electric motor is correctly sized for the job – if the power supplied is about the same or greater than the rated kW for the motor, the motor is undersized and at risk of burning out.

Meters operate with different tariffs. Electronic types, such as the top picture, may have a separate register for each tariff, and each register is read separately from the one meter. For example, the off-peak tariff may be given register '203', and full tariff may be '126'.

Mechanical or disc meters, such as the lower picture, more commonly have one meter for each tariff.

There also may be one for each phase of a 3-phase power supply, in which case you should add the readings from each meter, provided you measure each meter at the same time and for the same length of time. If in doubt about how to read your meters, check with your electricity supplier.

Table 1.8.6. Calculate power supplied to pump.

	Example
Power supplied to motor (**Ps**), from above	120.8 kW
Electric motor efficiency (**Me**) Table 1	90% (0.9)
Drive factor (**Df**) Table 4	Gear drive = 0.95
Power supplied to pump (**Pp**), after derating	Ps × Me × Df = 120.8 × 0.9 × 0.95 = 103 kW

Table 1.8.7. Calculating actual pump efficiency.

Actual pump efficiency (**Pe**) (using re-arranged power equation)	Q × H ÷ P = 1076 × 7 ÷ 103 = 73%
Compare actual efficiency with theoretical efficiency	73% is less than the 89% on the pump curve, so improvements can be made!

Step 2.2 – Determining energy usage – Diesel Engines

A similar process can be done for pumps with diesel engines. Greater caution is needed, however, because there are more assumptions in this process.

The main assumption is that the diesel engine itself is running efficiently – if it is actually performing poorly, the results will indicate that the pump is running less efficiently than it really is. The measure of efficiency for internal combustion engines is called Specific Fuel Consumption. It is usually reported as litres of fuel used (L) divided by the energy (kWh) produced. It is difficult to measure so a reasonable estimate (at sea level at 25°C) for engines in good condition is about 0.25 L/kWh for most large diesel engines (over 70 kW) and 0.3 L/kWh for smaller engines.

The process requires some way of measuring diesel fuel consumption. The example below assumes the fuel tank is supplying only one engine and that it has a calibrated dip stick. The accuracy of the result will depend on how accurately the fuel consumption can be measured. (Calibrated dipsticks and flow meters can be obtained from retailers such as Australian Fuelling Systems & Equipment www.fuelequipment.com). (If using in-line fuel flow meters to obtain fuel consumption, ensure fuel return is taken into account.)

The Power equation is slightly modified to account for conversion of diesel fuel to energy:

$$Pe = (272 \times H \times SFC) \div (L/ML \times Dr \times Df \times Dt)$$

Where:

272 – a conversion factor

SFC – Specific Fuel Consumption (as above) (L/kWh)

L/ML – Fuel use per ML of water pumped (L/ML)

H – Head

Dr, Df, Dt – De-rating factors.

Table 1.8.8 - Determining diesel fuel consumption

Fuel use	EXAMPLE
Start time (**T1**) First dipstick/meter reading (**F1**) Finish time (**T2**) Second dipstick/meter reading (**F1**)	2.12 pm 1800 L 8.12 pm 1634 L
Fuel consumption (L/h)	**EXAMPLE**
(F1 – F2) ÷ (T2 – T1)	(1800 – 1634) ÷ (8.12 – 2.12) = 27.7 L/h

Table 1.8.9. Calculating actual pump efficiency.

Specific Fuel Consumption (**SFC**)	0.25 L/kWh
Water flow rate (**Q**)	1076 L/sec = 3.875 ML/h
Fuel Use per ML Water Pumped = Fuel (L/h) ÷ Q (ML/h)	= 27.7 ÷ 3.875 = 7.15 L/ML
Pressure gauge or Delivery Head (**DH**)	7 m
Suction lift (**SuH**), assumed value	0 m
Total head (**H**), DH + SuH	7 m
Altitude derating (**Dr**), at 200m (Table 2)	0.99
Temperature derating (**Dt**), 30°C (Table 3)	0.964
Transmission (**Df**), gear drive (Table 4)	0.95
Conversion factor	272
Pump efficiency %(**Pe**) = (272 × H × *SFC*) ÷ (L/ML ×Dr × Df × Dt)	= (272 × 7 × 0.25) ÷ (7.15 × 0.99 × 0.95 × 0.964) = 476 ÷ 6.482 = 73%
Compare actual efficiency with theoretical efficiency	73% is less than the 89% on the pump curve, so get pump checked further!

Because this efficiency figure is approximate, use it as a guide only. If it is much worse than the manufacturer's performance sheets indicate, have the pump checked by a pump specialist.

Is it worth taking action? – determine the cost/benefit

Determining if taking some action to improve your pump's performance is economically worthwhile involves some simple calculations.

The money lost by operating an inefficient pump can be substantial. The more water you pump when you use an inefficient pump the more money you lose.

Inefficient pumps may impact upon your enterprise in many ways, including:

- Increased fuel costs
- Production losses – reduced yield and/or quality
- Increased water use
- Environmental cost – greenhouse gas emissions in extra energy consumed

Calculating cost per megalitre pumped (electric):

Using the example data from the previous section:

First calculate the energy used per ML of water pumped. This can be calculated as follows:

Power supplied (kW) ÷ Flow Rate (L/s) ÷ 0.0036 (to convert L/s into ML/h)

Table 1.8.10. Calculating energy use per ML of water pumped (electric)

Power Supplied (Ps)	120.8 kW
Flow Rate (Q)	1076 L/s
Energy used per ML pumped (Z)	Ps ÷ Q ÷ 0.0036 = 120.8 ÷ 1076 ÷ 0.0036 = 31.2 kWh/ML

The above figure is useful for comparing your pumping performance regardless of energy costs.

The cost of pumping can now be calculated from your electricity tariff. If your electricity supplier has different tariffs for day, off-peak, weekends etc., base your calculation on the tariff most applicable to obtain a good estimate, or work out the cost for each tariff and time of operation to get an exact cost.

Table 1.8.11. Calculating the cost of pumping (electric)

Pumping cost per megalitre @ 15c per kWh G = Z × $	G = 31.19 × $0.15 G = $4.68 / ML
Pumping cost per ML per metre head = G ÷ H	= $0.67 / ML / m head

Calculating cost per megalitre pumped (diesel):

Using the diesel example from the previous section.

Table 1.8.12. Calculating the cost of pumping (diesel)

Cost of diesel per litre on-farm	$ 1.10 /L
Pumping cost per ML (G), L/ML × cost	= 7.15 × 1.10 = $7.87 /ML
Pumping cost per ML, per metre head = G ÷ H	= 7.87 ÷ 7 = $1.13 / ML / m head

Determining the cost/benefit of improving pump efficiency:

Using the diesel example from above; if your pump is 73% efficient and your pumping cost is $7.87/ML, how much would be saved by improving the efficiency to the original design efficiency of 89%?

Saving per ML

= $7.87 – ($7.87 × 73 ÷ 89)

= $7.87 – $6.46

= $1.41

For a season where 1200 ML are pumped, the total cost saving would be:

$1.41 × 200 = $1692.00

If the cost of replacing the pump is $9,500 and the impeller $1,800, the cost of replacement is recovered in less than 6 seasons and repair in a little over 1 season.

Notice that a **reduced pump efficiency** of 16% (89% down to 73%) **increases** the cost of pumping by 22% (from $6.46 to $7.87 per ML).

Additionally, production losses from poor operation of a pressure irrigation system are likely to far exceed these pump operation losses, so serious consideration would be given to replacing the impeller earlier.

Pump selection using performance curves

Do not make your choice of a pump simply on cost. The pump on sale at the local supplier or the second-hand one for sale next door is unlikely to meet the demands of your system and crop.

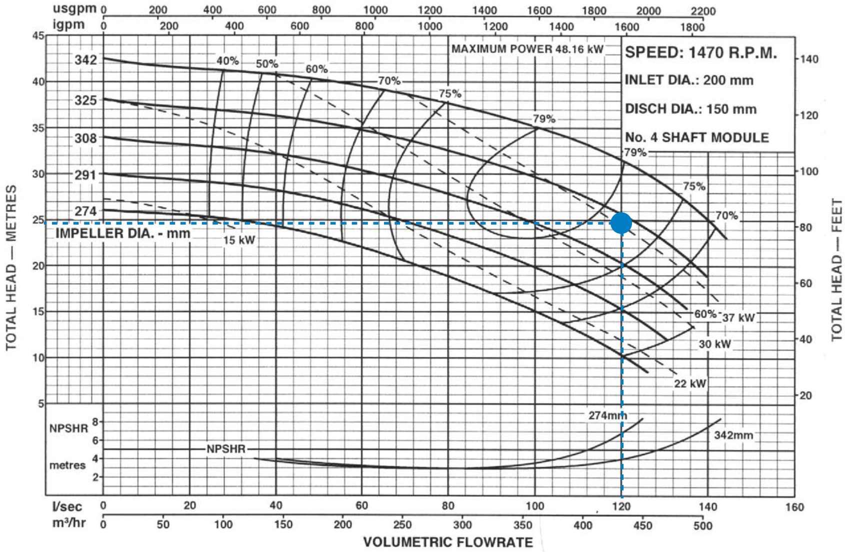
1. Select the duty point

To select a pump, the duty point must first be known. The pump must be matched to the requirements of the irrigation system, not vice-versa. For a new irrigation system, the flow rate (Q) and total head (H) should be readily obtained from the irrigation design. For an existing system, measure them using the methods described earlier.

The duty point will be the intersection of the flow rate and the total head. Once the duty point is known, locate it on the H-Q curve for a pump. If you cannot locate the duty point on a particular curve, then that pump will not suit your task. For example, for a centre pivot with a duty point of 120 litres per second and pump pressure gauge reading or Total Head of 250 kPa (25 metres):

Note the impeller size and speed – for

Figure 1.8.9. Select the duty Point



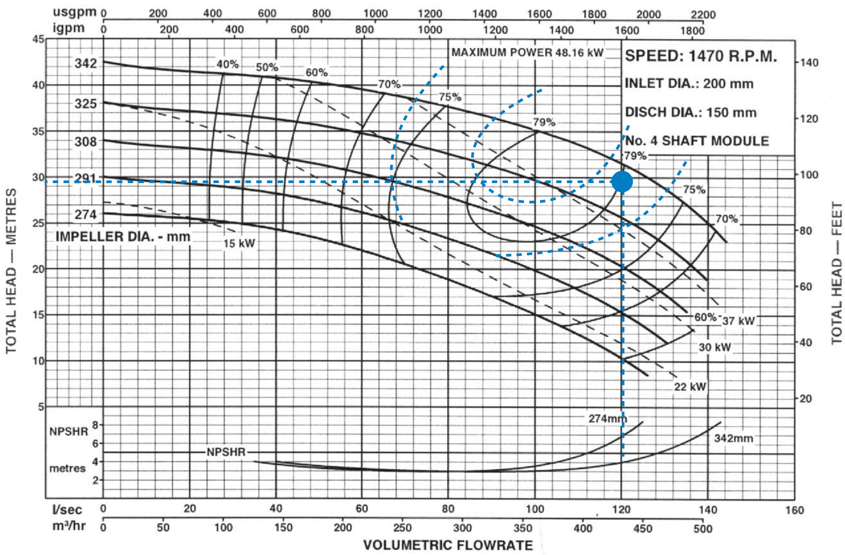
this example the size is 325 mm and the speed is 1470 rpm.

2. Check the pump efficiency

When the duty point is located on the H-Q curve, find the corresponding efficiency on the efficiency curve. The aim is to have the efficiency as high as possible. If it is below 65%, try another pump/curve. For most irrigation systems, you will find a number of pumps over 65% – select the highest efficiency unit that has a competitive price. In the example below, the efficiency is 78%.

3. Check the suction lift

Figure 1.8.10. Check the pump efficiency



Required. The theoretical maximum vertical height any pump can lift water is about 10 metres at sea level, less than 10m at higher altitudes. The NPSHR is the amount of this 10 metres used by the pump just getting the water into it. If the suction lift or height is more than what is left, the pump will cavitate or simply not pump water.

Suction lift is the vertical distance between the water level and centre of the pump. It can be measured directly or read from the irrigation design plan. The suction lift often varies with river height, storage level, bore depth, etc. so the greatest likely figure should be used for pump selection.

Read the NPSHR from the curve, subtract it and the Friction Head of your suction pipe from the average atmospheric pressure (10 m at sea level), and check that it is less than your suction lift. If not, try another curve. Pressure variation due to altitude is indicated in the table.

Altitude (m)	Atmospheric pressure (m)
Sea level	10
500	9.5
1,000	9
5,486	5

Max Suction Lift
= Atmospheric pressure – NPSHR – suction pipe friction
= 10 – NPSHR – suction pipe friction

For the example below, the NPSHR for a 325 mm impeller is 5 m.

Max Suction Lift
= 10 – NPSHR – suction pipe friction
= 10 – 5m – 1m (est) = 4m

What is Net Positive Suction Head (NPSH)?

Net Positive Suction Head (NPSH) is the head that causes water to flow into the pump. The water is pushed by the atmosphere into the pump because there is negative pressure, or suction, at the eye of the impeller.

Net Positive Suction Head Required (NPSHR) is a function of pump design and varies between make of pump, type of pump, speed and capacity. This value is usually found on the pump performance curves.

Net Positive Suction Head Available (NPSHA) is the available head at the suction flange of the pump and is a function of the suction pipe system. NPSHA must be greater than the NPSHR. A conservative minimum is 1 metre.

Figure 1.8.11. Check the suction lift

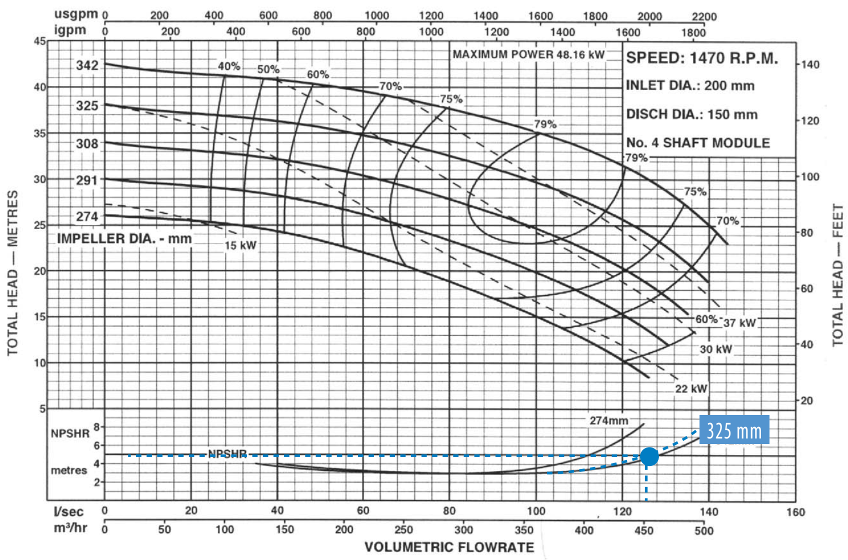
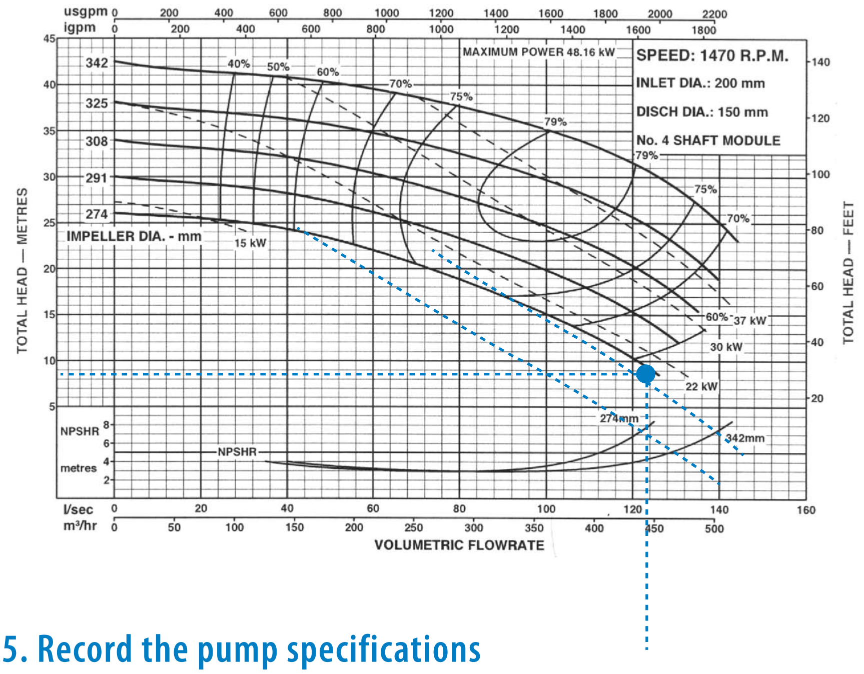


Figure 1.8.12. Determine the pump power required



5. Record the pump specifications

Having found a suitable pump, write down all the specifications. There are many pumps from many manufacturers available, often appearing very similar, so every important piece of information should be recorded to ensure you get the pump you've selected.

Table 1.8.13. Pump specifications

	Pump Choice 1	Pump Choice 2	Pump Choice 3
Discharge Q (L/s)	120 L/s		
Total Head H (m)	25 m		
Pump Brand	Pumpit		
Pump Model	Whoosher		
Impeller Size (mm)	325 mm		
Impeller type	Fully enclosed		
Pump Speed (rpm)	1470 rpm		
Efficiency Pe (%)	78% (0.78)		
Nett Power required (kW)	38 kW		
NPSHR (m)	5 m		
Inlet size (mm)	200 mm		
Outlet size (mm)	150 mm		
Transmission	Direct drive – electric v-belt – diesel		

6. Determine the drive unit size

Double check the power required at the pump by calculation:

Power (kW) = Q (L/s) × H (m) ÷ Pe ÷ 100

For our example:

Power = 120 L/s × 25 m ÷ 0.78 ÷ 100

= 3000 ÷ 0.78 ÷ 100 = 38.5 kW

It is advisable to choose a motor or engine that provides for additional power in reserve. This means the power unit will not be struggling to do its task, and as it ages it will still perform satisfactorily. As a guide, for electric motors add 10% to the calculated figure, and 30% for internal combustion engines:

Size of electric motor to purchase = Pump power + derating factors + 10%

Size of diesel engine to purchase = Pump power + derating factors + 30%

Table 1.8.14. Derating – electric

Motor efficiency Me (as a decimal)	**0.88**
Submersible?	**No**
Df (as a decimal)	**1.0**
Electric motor power required (kW)	**= kW ÷ Me ÷ Df (+ 10% reserve)** **= 38.5 ÷ 0.88 ÷ 1.0 (+ 10%)** **= 43.8 kW (+ 4.4 kW) = 48.2 kW** **55 kW** is the nearest stock electric motor

Table 1.8.15. Derating – diesel

Altitude (m) Dr	**200 m – 0.99**
Turbo?	**Yes**
Air temperature (°C) Dt	**40 °C – 0.892**
Df (as a decimal)	**0.9**
Diesel engine power required (kW)	**= kW ÷ Dr ÷ Df ÷ Dt (+ 30% reserve)** **= 38.5 ÷ 0.99 ÷ 0.9 ÷ 0.892 (+ 30%)** **= 48.4 kW (+ 14.5 kW) = 63 kW**

Pump maintenance

All pumps and their power sources need to be correctly maintained for efficient operation. Any change can have a major effect on operating efficiency. A check of your pump and fittings should be carried out before each irrigation season.

Table 1.8.16. Installation and maintenance checklist

Things to do:	Things not to do:
• site the pump as close as practical to the water • make sure suction and delivery pipes do not strain the pump casing • check that all pipe connections are tight and suction lines are airtight • use a strainer recommended by the pump manufacturer • anchor the pump securely so that it doesn't move during operation • work the pump within its limits • provide ventilation for the motor or engine • keep pump and motor connection aligned • make sure pump is primed before starting • keep the strainer clean • service the pump regularly	• do not operate pump without water • do not operate pump for long if discharge valve is closed • do not operate pump if strainer is blocked • do not operate pump if it is vibrating excessively • do not install suction pipes so that air can build up in them.

Managing water in plant nurseries by C. Rolfe, W. Yiasoumi, E. Keskula, NSW Agriculture 2000, p.196

Suction

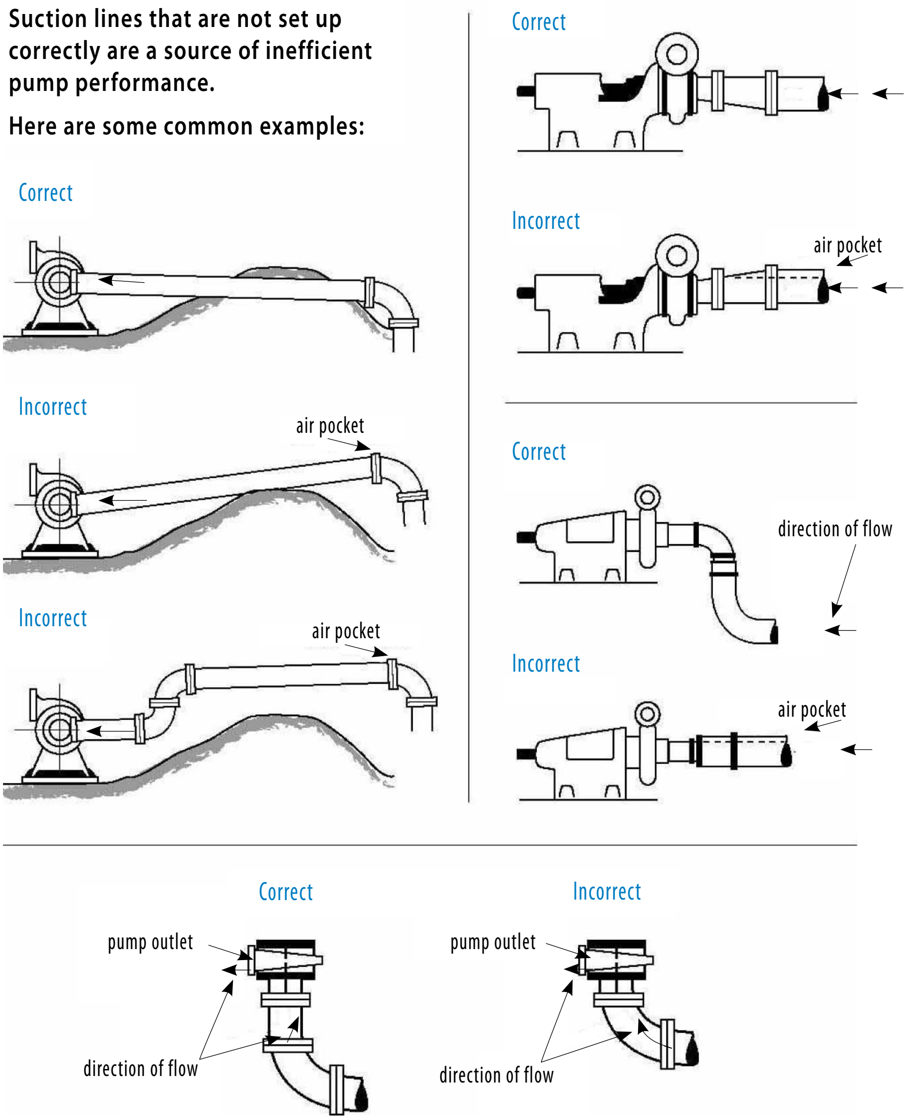
A major cause of poor pump performance is problems in the suction line. Things to look for on the suction side of the pump are:

- *Suction lift too high*
  About 4.5 metres from the water level to the pump is generally the maximum recommended lift. This will vary with the pump and its duty and should be checked with your local pump distributor.
  Excessive lift causes cavitation and perhaps damage to the pump. If the pump is cavitating it usually sounds like it is pumping gravel.
- *Air pockets*
  Incorrect installation of suction pipes and fittings may cause pockets of trapped air. These reduce the effective internal diameter of the pipe or fitting and create additional friction loss.
- *Air leaks at joints*
  Air entering through joints or through the footvalve causes a severe drop in pump performance and causes damage to the pump itself. Check all joints for leaks and if necessary replace any worn flange gaskets.
- *Footvalve*
  Ensure that the footvalve is sufficiently submerged below water level to prevent a vortex of air being drawn into the suction. A minimum depth of about 0.5 metres is desirable. Ensure the footvalve is not blocked with sand, weed, algae, or other foreign matter.

Figure 1.8.13. Pump suction line setup.

Suction lines that are not set up correctly are a source of inefficient pump performance.

Here are some common examples:



Pump

Main check points on the pump are:

- *Bearings*
  A screwdriver (preferably one with metal through the handle) held against the pump near the bearings and also held against the ear will help check for bearing wear. A smooth hum will indicate the bearings are sound. A grinding noise, rattle or bumping noise indicates bearings are worn. Bearings should be lubricated to manufacturer's recommendations. Hot bearings can be an indication of too much grease. If the bearings are oil lubricated the oil should be changed annually or every 1000 running hours, whichever comes first.
- *Packing Glands*
  The packing gland material should be replaced periodically and the gland follower should not be too tight. A steady drip from the gland is normal and is an indication of correct adjustment. If the pump at the packing gland is running hot it indicates the gland follower is too tight and should be loosened to allow more water leakage.
- *Mechanical Seals*
  If the pump has a mechanical seal, as opposed to a packing gland, then leakage indicates the mechanical seal to be worn and in need of replacement.
- *Impeller*
  The impeller should be inspected for general wear of the vanes and the face. The clearance between the impeller wear ring and suction eye ring should be measured accurately. Generally this clearance should be in the range of 0.13 to 0.25 mm. This should be confirmed with the pump manufacturer. A clearance outside the pump manufacturer's range indicates new wear rings or a new impeller are needed.
- *Pump Shaft*
  This should be checked for scoring and straightness. Shaft straightness can be checked by using a dial indicator on the impeller end of the shaft while the shaft is supported on the bearing housing. The total run-out should not exceed 0.05 mm.

- *The Pump Bowl*
  The pump bowl, and also the impeller, should be cleared of any build-up of rust or corrosion. If there is wear or damage to the metal it can often be repaired by the use of a Water Resistant Epoxy such as Devcon®, Vepox cc 65® or Chesterton® Pump Repair Compound.
- *Seal & 'O' Ring*
  The condition of the seal at the drive end of the shaft and the 'O' ring on the back cover should also be checked for wear and replaced if necessary.

Cavitation

Cavitation occurs when a pump has to get water from a height which exceeds its suction lift ability ie. the Net Positive Suction Head (NPSH) is not adequate. If cavitation is occurring during normal irrigation, the suction lift is probably too high. Cavitation will damage your pump, decrease its performance and ultimately limit its life. A cavitating pump will usually vibrate and make a noise like gravel rattling in a drum.

Cavitation occurs because in the suction line the pressure on the water is reduced below atmospheric pressure. This causes the water to boil at ambient temperature and create tiny bubbles of vapour. When these bubbles reach an area of high pressure (at the face of the pump impeller) they collapse (implode). These implosions cause pitting and eventually holes in the impeller.

Cavitation is sometimes experienced when filling a pressure line at the start of an irrigation. Because the pressure takes a little while to reach operating level, the Total Head is temporarily low, and the flow rate is higher than the design duty. The higher flow increases the friction head in the suction line and fittings. This causes a greater pressure drop in the suction line, which may result in cavitation. To overcome this, control the filling flow rate by closing the gate valve at the pump before starting up, and opening it slowly as the pipe fills.

Cavitation may also occur if the flow rate has increased, for example, through worn sprinkler nozzles, leaks, or extra sprinklers being added.

Common solutions for cavitation are to relocate the pump to a lower level or alter the pump duty, possibly by making a better pump selection or restoring the irrigation system to its original design. Seek the advice of an experienced designer.

Further Information

A range of pump factsheets can be found online, including:


AGFACTS
Selecting an irrigation pump

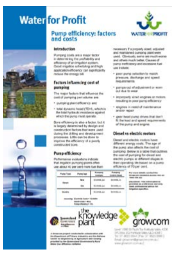
NSW Department of Primary Industries:

[Selecting an Irrigation Pump]

[How much does it cost to pump?]

[Is your diesel pump costing you money?]

[How efficient is your pump?]


Water for Profit
Pump efficiency: factors and costs

Growcom (horticulture):

[Pump Efficiency (under the heading 'System Evaluation']

1.9 Using PAM in irrigated cotton

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Key points

- Polyacrylamide (PAM) is used in irrigation fields to minimise soil erosion. Increases in infiltration and decreases in runoff concentrations of sediment and contaminant also typically occur.
- Rigorous scientific trials conducted on PAM use in the USA have been undertaken using drastically different furrow irrigation systems to those employed in the Australian Cotton Industry. The performance of PAM under these Australian conditions may be significantly different.
- Understanding current furrow irrigation performance is essential when considering PAM for in-field use, as slower advance rates are likely to increase total water use and decrease water use efficiency in all but low infiltration soils.
- When used in the right circumstances (eg. soils with low infiltration rates), PAM has the potential to dramatically decrease sediments, nutrients and various contaminants in runoff and improve irrigation infiltration.
- When used incorrectly, PAM has the potential to dramatically decrease irrigation performance and increase water use.
- PAM also has potential application for evaporation and seepage control although the effectiveness under typical Australian cotton industry conditions is not well known.

Introduction

Polyacrylamide (PAM) is a long chain hydrocarbon of high molecular weight that has been used extensively across numerous industries for many decades. Some of the current uses of PAM include:

- treating potable water,
- dewatering sewage sludge,
- food processing practices,
- paper and adhesive manufacture (including food grade paper products),
- cosmetic manufacture; and
- mining and drilling operations.

PAM is generally used as a settling agent. When added to a solution it flocculates (clusters together) fine particles which can then settle out of the solution. Hence when added to irrigation water, PAM binds the fine clay and silt particles together. The resulting action is twofold; soil structure is stabilised, reducing the detachment and transport of sediment from the soil surface, whilst any detached particles are flocculated and can settle out of the irrigation stream.

There are actually hundreds of different formulations of PAM including cationic, neutral and anionic varieties with molecular weights ranging from 1 to 20 million. PAM rarely contains hazardous elements (e.g. heavy metals or radionuclides) and due to its low toxicity to the environment and organisms, it is believed to have low environmental and public health impacts (Misra and Hood, 2007).

PAM used for irrigation is mostly anionic and may be provided in either fine granular, liquid or emulsion forms. Some cationic and neutral varieties are not suitable as they are not only less effective but may have environmental toxicity issues which are not present with anionic PAM when used at recommended rates. Appropriate PAM formulations are typically referred to as 'linear' or 'non-cross linked'. 'Cross linked' or 'super water absorbent' PAM's have a different function and should not be used for erosion control purposes.

Typical application rates of PAM in irrigation application systems are in the order of only a few kilograms per hectare. Often subsequent irrigations require lower application rates and so the typical seasonal application may only be five or ten kilograms per hectare. For applications in evaporation or seepage control the applications may be an order of magnitude higher.

Sufficient turbulence or agitation must be provided at the application point to dissolve granular PAM to the required concentration.

PAM use in Irrigation

The properties of PAM provide for a number of irrigation applications. As a flocculating agent, introducing PAM into irrigation water allows water borne soil colloids to fall out of suspension and remain in the field rather than being transported from the field in runoff. PAM can also act to stabilise soil structure, inhibiting soil breakdown and dispersion, and therefore is useful to maintain or improve infiltration in soils that are prone to sealing.

In higher concentrations, PAM also increases the viscosity of the water solution which has been proposed to have benefits in reducing evaporation and, in combination with the deposition of sediment, seepage in channels and storages.

Erosion Control

When PAM is applied to irrigation water, erosion from irrigated fields is reduced as the PAM enables clusters of soil particles to form which can then settle out of the irrigation water, reducing their transport from the field.

Trials in the USA have indicated reductions in runoff sediment of up to 94% through the use of PAM. The method of application involved dissolving 10 kg/ML of PAM in the irrigation water during the initial advance only. After runoff begins, PAM dosing is ceased. The resulting dose was generally 1-2 kg/ha. Where furrows were not disturbed, the erosion control during subsequent irrigations, without PAM application, was typically reduced by half.

The effectiveness of the PAM application for freshly formed furrows was found to vary according to inflow rate, PAM concentration, duration of furrow exposure and total amount of PAM applied. These variations may have dramatic impacts on the adoption of these results in Australia as the test conditions involved short fields (175 - 264 metres) and flow rates in the order of 13 – 38 L/min compared to the much longer field lengths (~400 – 1600 metres) and higher flow rates (> 60 L/min) typically employed in the Australian Cotton Industry. Flow rates in excess of 200 L/min are not uncommon. The performance of PAM under these conditions may be considerably different.

Australian trials have indicated reductions in erosion from furrow irrigation events at flow rates of up to 120 L/min using either wheat stubble or PAM. Accordingly, levels of some contaminants, particularly endosulfan, were also effectively reduced using these erosion control methods. However other contaminants such as metolachlor, which are not as strongly associated with soil particles, were not effectively controlled.

Trials in irrigated cotton fields in Emerald showed a reduction in tailwater sediment concentration of 80% with PAM concentrations of 0.5 to 1 kg per hectare (Waters, 2001). Misra and Hood (2007) report that Hugo (1999) obtained similar results in trials at Warren and Kingsthorpe, although this outcome in the Warren trial required a PAM application rate exceeding 3 kg per hectare. However all of these trials also found that erosion due to rainfall was not significantly influenced by the use of PAM during irrigation events. Misra and Hood (2007) also report on some further results from Australian studies.

Modifying Soil Infiltration Characteristics

PAM is also commonly used in irrigation to increase soil infiltration, which is thought to be achieved by both increasing soil surface stability and by decreasing the amount of suspended solids, which results in fewer soil pores being blocked by fine sediments.

In some hard setting or sodic soils, where obtaining sufficient infiltration is problematic, such an increase in infiltration may be desirable. In these cases, PAM can help to improve infiltration and reduce runoff losses. Similarly, where gypsum is used to reduce surface sealing, PAM may be useful to help improve infiltration without the amount of salt loading inherent in the continual use of gypsum.

However, most soils within the cotton and grains region are not of this type and in fact generally exhibit excellent infiltration properties. In such soils, which includes most heavy clay soils in this region, additional infiltration may encourage waterlogging, deep drainage losses and may also decrease irrigation performance.

When PAM use increases infiltration, this is reflected in the slowing of the advance of furrow irrigation water. However for most cotton growing soils, surface irrigation performance evaluations have typically indicated adequate soil infiltration rates and, in fact, water use efficiency will often increase through speeding up the irrigation advance (achieved with higher flow rates and shorter irrigation durations). Hence the use of PAM in such situations is likely to act against the commonly employed performance improvement tactics and may decrease water use efficiency if the system is not adequately analysed beforehand.

Successful application of PAM to modify soil infiltration characteristics is further complicated by the mix of results that can be obtained. For example, instead of increasing infiltration, Misra and Hood (2007) reported instances of soil infiltration being reduced through timing of application, incorrect PAM dosing or application to soils which already exhibit soil structural damage.

For these reasons, it is strongly recommended that where PAM is being considered for the purposes of modifying soil infiltration properties, current irrigation performance is first measured and independent advice is sought regarding the appropriateness of PAM application for the desired purpose.

Seepage and Evaporation Control

There has also been interest in the use of PAM for control of evaporation and seepage from storages and channels.

For evaporation control, it is thought that PAM may be able to reduce evaporation by increasing water viscosity. Trials at the National Centre for Engineering in Agriculture in small scale tanks of clean water showed evaporation savings of between 31 and 43% when applied at a concentration of 100 parts per million. However the level of potential savings under on-farm conditions is not clear.

Surprisingly, considering PAM may be used in fields in an attempt to increase infiltration, high application rates in channels and storages is believed to offer the potential to reduce seepage, The level of seepage reduction will most likely depend on the type, size and amount of suspended soil particles and the concentration of the PAM solution. Whilst there has been some investigation of the success of PAM for such applications in the US and to some extent in southern Australia, there has been limited investigation in cotton growing regions and the small amount of work that has been conducted has shown mixed results. Further information on PAM application for seepage reduction is included in WATERpak Chapter 1.6.

Environmental Considerations

As well as decreasing sediment runoff from irrigated fields, studies have shown that using PAM in irrigation water also decreases certain nutrient and pesticide loads in drainage waters. This is because many nutrients and pesticides are attached to the soil particles which are retained within the field. In addition, numerous microorganisms and weed seeds, typically removed in tailwater, remain in the field following PAM application. Minimising this movement results in significantly lower concentrations of pollutants in distribution systems and storages as well as off farm waterways.

When used at recommended rates, no significant negative impacts have been documented for crop species, soil microorganisms or aquatic macrofauna.

The movement of PAM from fields is minimal due to its attraction to sediment particles; as they settle out of the water stream, the PAM settles also. Trial results indicate that only 3-5% of the PAM applied to a field leaves in the tailwater and this volume travels no further than 100-500 metres along the tail drain. PAM in soil gradually breaks down at about 10-20% per year due to physical, chemical and biological activities.

Important Considerations

1. The biggest consideration facing the use of PAM on fields within the Australian Cotton Industry is its effect on furrow irrigation water use efficiency. Recent furrow irrigation trials have indicated that in many situations, water use efficiency is currently compromised through advance rates that are too slow, leading to poor uniformity, over application and extended periods of water logging. PAM used in these situations would likely exacerbate the problem by slowing advance rates even further.

   However there is quite probably potential for PAM use in some circumstances such as high slopes prone to erosion or soils with poor infiltration. The key is to gain an understanding of your situation before proceeding with PAM application. Surface irrigation performance evaluation (see WATERpak Chapter 5.3) is strongly recommended when considering PAM for in-field use as the potential for PAM to decrease water use efficiency if used in the wrong situations is significant.
2. In circumstances where furrow optimisation suggests that optimum flow rates are high enough that erosion is a significant issue, there may be potential to combine improved furrow irrigation practices and PAM application.
3. When using PAM, it is important to ensure that the first water to proceed down the furrow during the irrigation advance is of the correct PAM concentration. Any non-treated water that comes into contact with dry soil will start to degrade soil structure almost immediately, reducing the ability of PAM to stabilise soil structure and reduce erosion.

Case study: application of polyacrylamides in rural water use efficiency initiative demonstration sites

Irrigators in Queensland undertook several on-farm demonstrations of PAM use during the 2000 to 2003 summer irrigation seasons. The purpose of these demonstrations was to allow irrigators in the St George/Dirranbandi and Emerald regions to investigate the effect PAM had on improving infiltration and reducing erosion during cotton furrow irrigation events.

Due to lack of Australian research into the use of PAM in irrigated agriculture, irrigators and Rural Water Use Efficiency officers designed crude demonstrations (not rigorous trials) to monitor the effect of PAM treatments on fields with similar soil, design and management characteristics. The trials compared PAM treated and untreated fields or portions of fields. **The following results are simply recorded observations from the demonstration sites, and should not be taken out of the context of these demonstrations.**

In these demonstration sites, PAM was applied to irrigation water in the head ditch prior to siphons being started. The need for more investigation into application methods was highlighted due to some practicality issues

Case study: continued

St George

During the 2000/2001 season, a crude comparison of irrigation advance times for PAM treated and untreated furrow irrigation events demonstrated that it took approximately two hours longer for PAM treated water to reach the end of the furrow. It is therefore inferred that infiltration can be increased on these hard setting soils through the application of PAM. The effect on total water use, distribution uniformity and water use efficiency was not measured.

Emerald

In the Emerald irrigation subregion, trials investigated likely improvements in water retention in the root zone (due to PAM) and the effect on waterlogging and potential yield reductions. Advance rates and the amount of tailwater were measured in treated and untreated sites. Continuous soil moisture monitoring was undertaken at several soil depths at both sites.

Observed outcomes included an average advance time increase of one and a half hours over the furrow distance of 375 m at the treated site. This implies an increase in infiltration due to PAM application. Less tailwater was measured at the treated site, potentially indicating that less sediment and nutrients left the field. Soil moisture monitoring at the treated site indicated prolonged waterlogging, which may have contributed to yield loss.

Other investigations have demonstrated that PAM application may have been useful in ensuring even bed-wetting, thus assisting uniform germination and improved seedling establishment. In a demonstration of PAM on wheat an irrigator remarked on improved germination and seedling establishment, heavier seed heads, increased yield (0.25 tons/acre) and decreased water use (one whole irrigation) between a crop that was split into a treated section and a non-treated section.

Irrigators in the Emerald region are increasingly using PAM in their early irrigation particularly to save nutrients from being washed or leached away when the soil is still loose and fertiliser has just been applied.

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Section 2

Irrigation Management

2.1 Irrigation scheduling

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Key points

- Irrigation scheduling is the decision of when and how much water to apply to an irrigated crop to maximise crop productivity.
- Evapotranspiration (ET) is the combined loss of water to the atmosphere due to evaporation from soil and plant surfaces, and transpiration through plants.
- Crop evapotranspiration (crop water use) calculation and/or soil moisture monitoring can be used to schedule irrigations.
- Plant response to stress varies with the timing and degree of stress, and crop development stage.
- Soil probes do not need to be calibrated to analyse trends, but should not be used to infer total water use

Irrigation scheduling in Australia is difficult because of the variable and unpredictable climate, frequent summer storms and changes to prevailing air temperatures. Correct irrigation scheduling improves water use efficiency, reduces water-logging, controls crop canopy development, quantifies the effectiveness of rain and allows better management of soil structure issues.

This WATERpak topic provides an understanding of crop evapotranspiration and soil water. It also explains how to schedule irrigations and interpret the data collected from soil moisture measuring devices. Additional information that complements this chapter can be found in:

- *Chapter 2.3* - Tools and information for irrigation decision making
- *Chapter 2.4* - Measuring plant water status
- *Chapters 3.1, 3.2, and Section 4* - Irrigation management for cotton and various grains crops
- Chapters 2.2 and 3.3 - Managing Irrigation with limited water

Evapotranspiration (ET)

Evapotranspiration (ET)is the combined loss of water to the atmosphere due to evaporation from soil and plant surfaces, and transpiration through plants.

> **Transpiration** results from the vapourisation of water within plant tissues and its subsequent loss through the small openings on the plant leaf called **stomata**.
>
> **Evaporation** is the conversion of water from liquid to vapour.

Reference Evapotranspiration (ET_0) is the loss of water to the atmosphere by evaporation and transpiration from a reference crop resembling well-watered green grass with a uniform height of 120 mm. The concept of reference evapotranspiration is used to represent evaporative demand independent of crop and management characteristics at a particular location. By applying an appropriate coefficient, the reference ET value can be used to estimate crop evapotranspiration (ET_c) and the evaporation losses from storage and reticulation systems.

Crop Evapotranspiration (ET_c) describes the actual ET of a crop given standard conditions of optimum soil water, excellent management conditions, large fields and full production. Understanding and determining crop evapotranspiration is critical for scheduling irrigations to meet the crops water use demands and to optimise crop production.

The ET rate is normally expressed in millimetres (mm) per unit time (often mm/day) – it represents the amount of water evaporated from a cropped surface in units of water depth.

100 mm depth of water is equal to 1 ML of water per Ha

Factors Affecting Evapotranspiration

Weather

Radiation

Air temperature

Humidity

Wind speed

The evaporation power of the atmosphere is expressed by the reference crop evapotranspiration (ET_0), which represents the ET from a standardised vegetated surface (well watered grass). Calculation of ET_0 is generally performed by automatic weather stations, software packages or ET data providers (such as SILO). Some further information is included in Chapter 2.8.

The current standard for calculating ET_0 is the Penman-Monteith method – also referred to as the FAO 56 method. Calculations based on pan evaporation are no longer used as the standard.

Crop

Crop type

Variety

Crop Development stage

These factors affect the rate of ET_c from crops grown in large, well-managed paddocks. Differences in crop height, reflection, ground cover, resistance to transpiration, etc., will result in different ET_c levels in different crop types under identical environmental conditions.

Environmental and Management Conditions

The actual crop evapotranspiration may be influenced by factors that impact on the ability for the standard conditions mentioned above to be satisfied such as:

- Soil salinity
- Inadequate nutrition
- Soil compaction
- Diseases and pests
- Cultivation and irrigation practices
- Windbreaks which reduce wind velocities across the adjacent field
- Irrigation systems that apply water directly to the root zone of crops (limiting evaporation losses as soil surface is dry)
- Surface mulches which substantially reduce soil evaporation when crops are small.

Where these factors are significant, calculation of ET_c should be modified accordingly.

Determining Crop Evapotranspiration

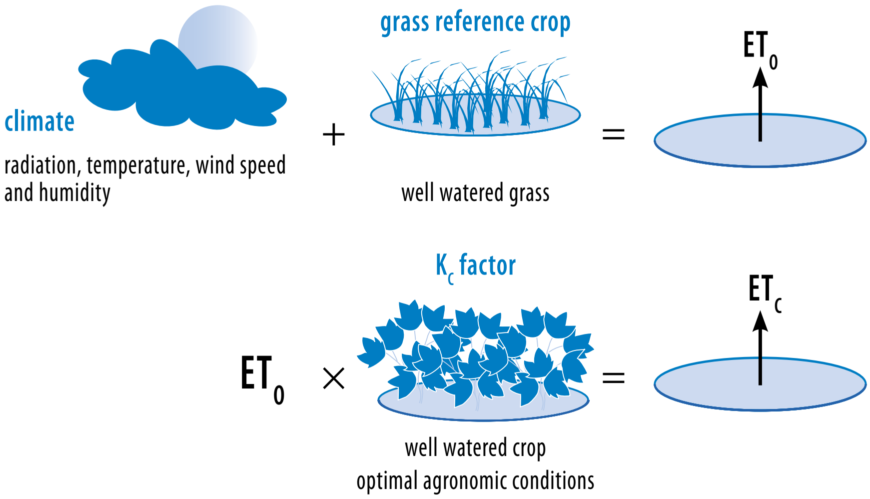
Evapotranspiration is difficult to measure, and is therefore only undertaken in scientific studies using methods such as the Bowen Ratio or Eddy Covariance. For practical purposes, reference evapotranspiration (ET_0) data is available from weather providers (e.g. Bureau of Meteorology or SILO) or from some automatic weather stations (AWS),

A Crop Coefficient (K_c) is used to convert the weather derived Reference Evapotranspiration (ET_0) to an estimate of Crop Evapotranspiration (ET_c) using the following formula:

$$ET_c = K_c \times ET_0$$

The relationship between Reference Evapotranspiration (ET_0) and standard Crop Evapotranspiration (ET_c) through the Crop Coefficient (K_c) is represented in Figure 2.1.1.

Figure 2.1.1. The relationship between Reference Evapotranspiration (ET_0) and standard Crop Evapotranspiration (ET_c)



Source: Allen, R.G. *et al* (1998) Crop evapotranspiration: guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper 56.

The K_c integrates the effect of characteristics that distinguish the crop from the grass reference crop used to calculate ET_0. Different crops have different K_c values due to different crop characteristics. The K_c value also changes over the growing season with changes in crop development and with changes affecting soil evaporation. Estimates of K_c values for the major irrigated crops are presented in Table 2.1.1.

Table 2.1.1: Crop Coefficients (K_c) for major irrigated field crops.

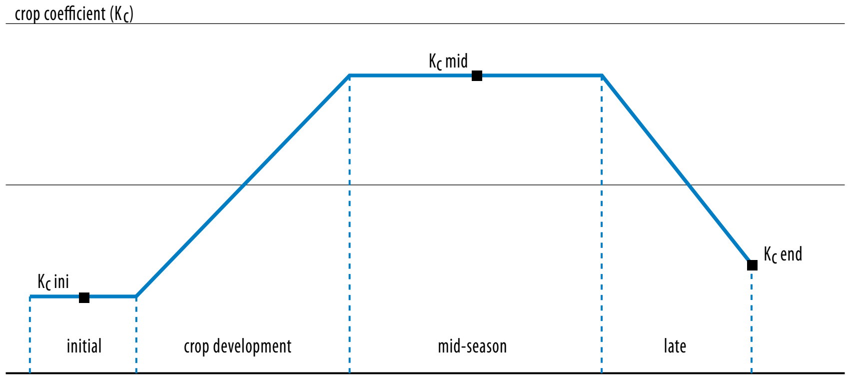
Crop	K_c initial	K_c mid-season	K_c end of season
Barley	0.30	1.15	0.25
Chickpea	0.40	1.00	0.35
Cotton	0.35	1.15 – 1.20	0.70 – 0.50
Maize	0.30	1.20	0.35
Navy bean	0.40	1.15	0.35
Peanut	0.40	1.15	0.60
Sorghum	0.30	1.00 – 1.10	0.55
Soybeans	0.40	1.15	0.50
Sunflower	0.35	1.15	0.35
Wheat	0.30	1.15	0.25

Source: Allen, R.G. *et al* (1998) Crop evapotranspiration: guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper 56.

The crop development stages used to select a K_c value (Figure 2.1.2) are:

1. Initial stage – planting until 10% ground cover.
2. Crop development stage – 10% to effective groundcover (around 70–80%).
3. Mid-season stage – 70–80% groundcover to the start of maturity.
4. Late season stage – the start of maturity until harvest.

Figure 2.1.2. Example Crop Coefficient curve.



Example:

We want to determine the crop water use over a period of a week in mid February for a crop of soybeans. The soybeans are in their mid-season phase, so the crop coefficient (K_C) will be 1.15 (from Table 2.1.1).

Daily crop water use (ET_C) = $ET_0 \times K_c$

The following table contains the ET_O data obtained from SILO as well as the calculations of daily ET_C:

Date	*ET_0*	*K_c*	*Daily Crop Water use ET_c mm/day*
15 Feb	*4.6*	*1.15*	*5.3*
16 Feb	*3.1*	*1.15*	*3.6*
17 Feb	*4.4*	*1.15*	*5.1*
18 Feb	*4.2*	*1.15*	*4.8*
19 Feb	*5.5*	*1.15*	*6.3*
20 Feb	*4.4*	*1.15*	*5.1*
21 Feb	*5.7*	*1.15*	*6.6*

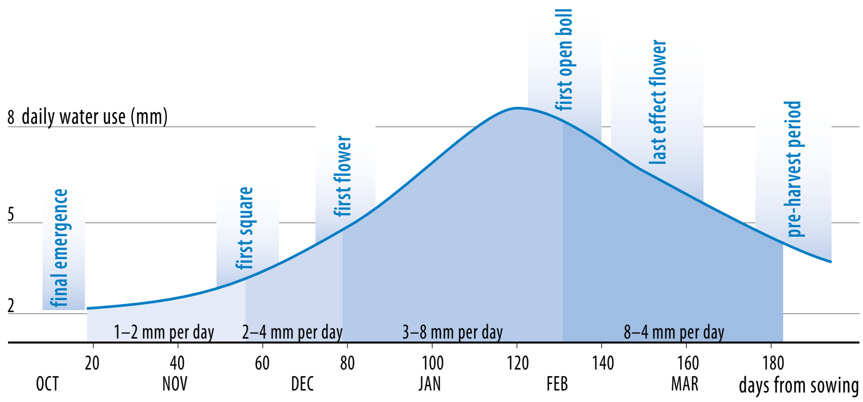
It should be noted that the method above uses standard crop coefficients which relate to crops under disease free, well fertilised, optimum soil moisture and full production conditions. Often crops do not meet these conditions, and the crop coefficient (K_C) can be varied under these circumstances to better reflect the actual crop conditions. However this may be difficult to do with accuracy, and usually involves at least some additional measurement, for example of leaf area index (LAI). Newly developed tools such as IrriSAT can use regular satellite imagery of the vigour of individual fields to provide an improved measure of K_c and hence ET_C.

Crop Water Use and Plant Growth

A crop's requirement for water changes throughout the growing season, following the pattern of evapotranspiration (Crop Water Use). The rate of evapotranspiration is determined primarily by meteorological factors and the availability of soil water. Total crop evapotranspiration will also vary with canopy size, or leaf area.

Using cotton as an example, the figure below shows that the period where crop leaf area peaks (3 to 5 weeks after the start of flowering) is also the time of maximum daily water use of between 8 and 10 mm (Figure 2.1.3).

Figure 2.1.3. Nominal seasonal Daily Water Use (mm/day) for cotton production.



The maximum demand for water also coincides with the growth period between peak flowering and early boll development. Exposing the plant to water stress at this stage of growth can result in significant yield reductions. The impact of water stress at different crop growth stages on final yield is directly related to the water demands expressed by the crop. Stress during periods of high water demand can produce large reductions in yield. Stress during peak flowering can double yield losses compared with early or late seasonal stress. The impact of any one stress period is increased if followed by further stress. Further information for cotton and grain crops can be found in chapters 3.1, 4.1, 4.2, 4.3 and 4.4.

The total seasonal crop evapotranspiration is an accumulation of the daily crop ET_C over the whole season. This figure will vary from crop to crop and from year to year, but will typically be within the range provided in Table 2.1.2.

Table 2.1.2. Water Requirements of Crops

Crop	Crop Evapotranspiration Requirement[1] (mm)	Peak Daily Water Use (mm/day)			Critical Irrigation Periods
		$ET_0 = 6$ mm	$ET_0 = 8$ mm	$ET_0 = 10$ mm	
Barley**	350 to 500	6.9	9.2		Shot – blade to late flowering
Chickpeas**	350 to 500	`6.0	8.0		4 to 5 weeks after flowering
Cotton***	650 to 770	6.9–7.2	9.2–9.6	11.5–12	Peak flowering and early boll development
Maize*	600 to 850	7.2	9.6	12	Tasselling through seed fill
Lucerne for hay**	750 to 1500	6.9	9.2	12	From one week after cutting to flowering
Navy beans**	300 to 450	6.9	9.2	11.5	Flowering
Peanut**	500 to 700	9.2	9.2	11.5	Flowering and pegging to pod maturity
Sorghum*	450 to 850	6.0–6.6	8.0–8.8	10–11	Boot to dough stage
Soybeans**	500 to 775	6.9	9.2	11.5	Flowering to leaf drop
Sunflower*	600 to 800	6.9	9.2	11.5	Once bud is visible, start of flowering and just after petal drop
Wheat**	350 to 500	6.9	9.2		Boot stage and flowering until soft dough stage

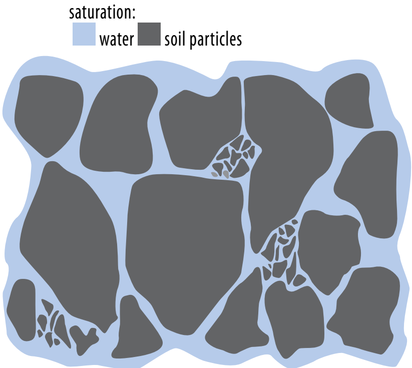
1. The crop evapotranspiration is the demand that must be met by in-season rainfall, irrigation and stored soil water at planting.

Sources: *Pacific Seeds 2006/07 Cropping yearbook. **Graham Harris, DPI&F, pers.comm. ***WATERpak 2001

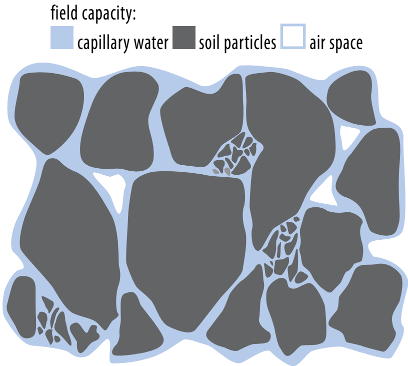
Understanding Soil Water

An understanding of basic soil water states is important for managing irrigation scheduling. Figure 2.1.4 illustrates the relationships between the terms described below.

Saturation may occur after heavy rain, during surface irrigation, or following over-irrigation. This is when even the largest pores are filled with water. When the soil is saturated, there is no air for the plant roots. This will stress many plants and is often described as waterlogging.



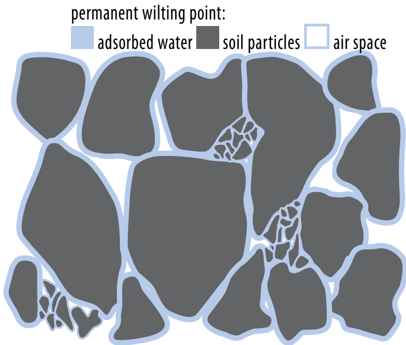
Field capacity (full point) occurs after large soil pores (macropores) have drained due to gravity. Depending on the type of soil, this drainage may take from a few hours up to several days. When the large pores have drained, the soil is still wet, but not saturated. The soil is said to be at field capacity. Field capacity in most soils is at a soil-water tension of about –8 kPa.



Refill Point (target deficit) is the point at which a particular crop finds it difficult to extract water from the soil and begins to stress, slowing crop growth. For most cotton and grain crops, this usually occurs when the soil water potential is between -60 and -100 kPa.

The refill point changes during the season. Young plants have small roots that only have access to a limited part of the soil profile. As the plant grows, the roots can access more of the profile and therefore tolerate a larger soil moisture deficit before reaching refill point. Determining the refill point can be achieved by measuring soil water potential or by analysing daily water use patterns to determine when the crop is finding it difficult to remove water. If irrigation is not applied prior to soil water levels passing an accurate refill point, then a yield reduction will occur, depending on the stage of the crop.

Permanent Wilting Point occurs when the soil reaches a point where the plant can no longer extract moisture. Once the soil has passed this point, water is held by the soil so tightly that the plant cannot extract it and will start to die.



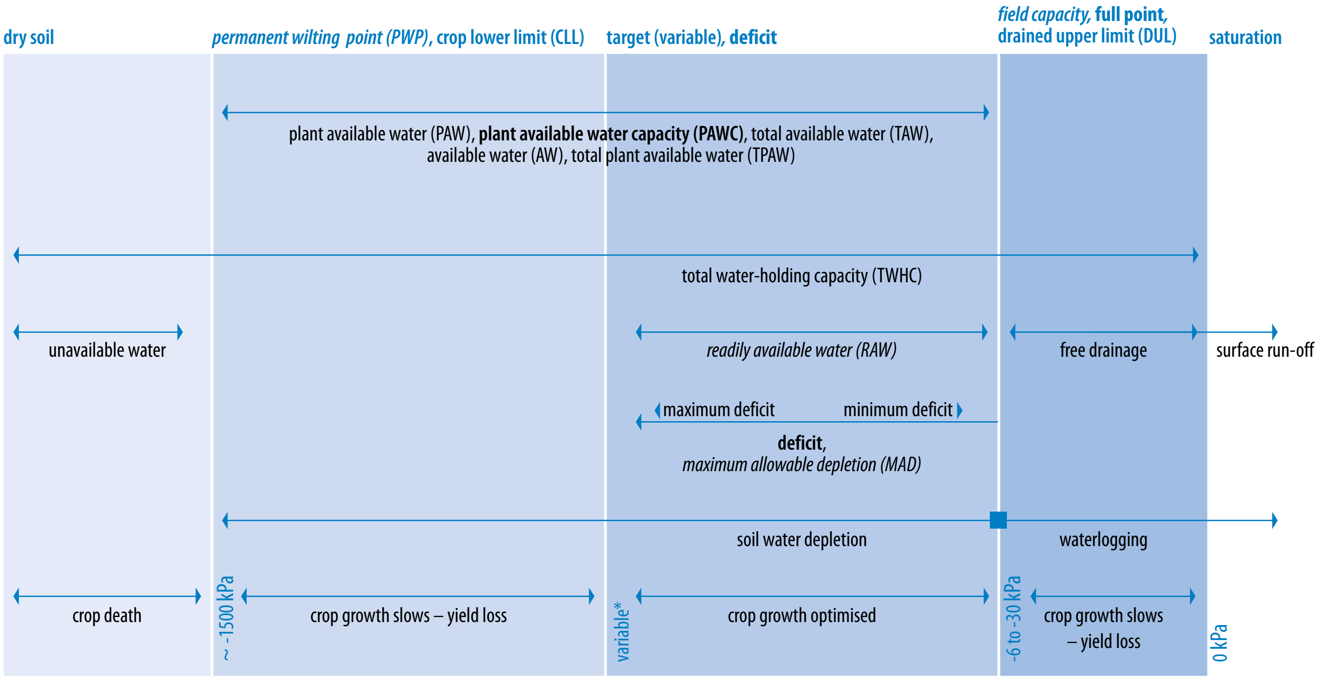
A note on deficit

The term deficit is often used in two ways:

1. It most often used to describe the current moisture status of the soil. In this usage, it suggests how much water would be required to fill the profile to the full point.

2. Deficit is sometimes also used interchangeably with the term Refill Point. This usage would be more appropriately termed Target Deficit as it is the deficit at which plant stress, and hence irrigation, is triggered.

Figure 2.1.4. Soil water terminology



Terms in *italics* are nationally adopted (ANCID); current cotton industry terms are in **bold**.

Units can be kPa, mm or percentage volumetric soil water (% VSW), depending on soil water measurement method.

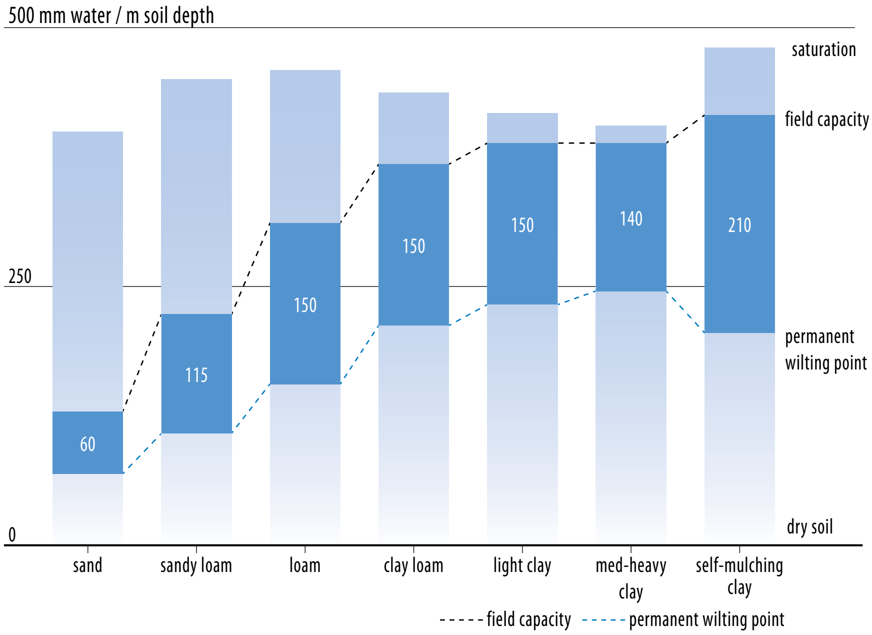
* variable suction levels depending on soil type and management

Source: David Williams

Most soils have a similar total water holding capacity, generally between 400 500 mm per metre depth of soil, as illustrated in Figure 2.1.5. However, the amount of water actually available for use by the plant varies greatly due to different soil textures and their influence on soil moisture.

The shaded section in the middle of each column shows the average amount of water available to plants. Water held below permanent wilting point is shown by the bottom section of each column, and free-draining water (above field capacity) is shown in the top section.

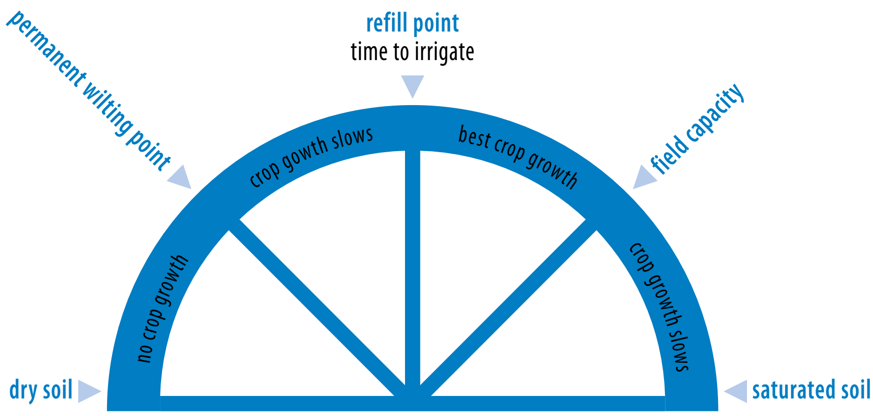
Figure 2.1.5. Total amount of water held in different soils



Plant Available Water Capacity (PAWC)

The amount of water held in the soil between field capacity and the permanent wilting point represents the Plant Available Water Capacity (PAWC). However irrigation scheduling decisions should be undertaken when the soil moisture is between the full and refill points, known as the Readily Available Water (RAW). This can be visualised like a fuel gauge as in Figure 2.1.6.

Figure 2.1.6. Soil Water '*Fuel Gauge*'



Scheduling Irrigations

Irrigation scheduling is the decision of when and how much water to apply to an irrigated crop to maximise crop productivity. Good scheduling should provide plants with water that is within a desired range and should limit over or under irrigation.

The advantages of irrigation scheduling include:

- The management of water between fields to minimise crop water stress and maximise productivity.
- Improvements in energy, water and labour efficiency through more effective irrigation.
- An increase in Water Use Efficiency and fertiliser effectiveness through reduced surface runoff and deep drainage.
- Increased net returns through increased yields and improved crop quality.
- A minimisation of water-logging problems.
- Assisting control of root zone salinity problems through controlled leaching.
- Additional crops through savings in irrigation water.
- The ability to precisely control availability of soil moisture when using precision application techniques.

It is very important to remember that irrigation scheduling is strongly related to system performance. Therefore system efficiency and uniformity should be taken into account when making irrigation scheduling decisions.

The following section will outline a number of methods for scheduling irrigations and will focus on the tools available and how these are used. It should be noted that a range of other factors should also be considered when scheduling an irrigation including;

- Total water availability (WATERpak Chapters 2.2, 3.3)
- Crop growth status and potential yield (WATERpak Chapters 3.1, 4.1, 4.2, 4.3, 4.4)
- Predicted rainfall and future temperatures (WATERpak Chapter 2.3)
- Practical farm management logistics such as the physical movement of water

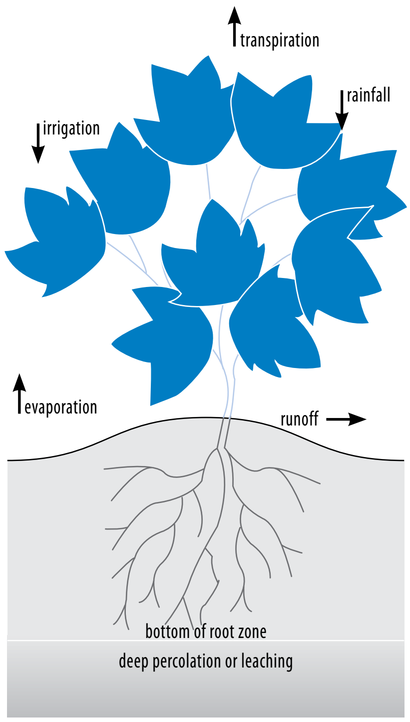
Scheduling methods & tools

ET Based Methods

Crop evapotranspiration is calculated from climatic factors and crop coefficients as described above. This data can be used for daily accounting of the amounts of water entering and leaving the crop root zone.

This procedure is based on estimating the soil water content in the crop root zone by balancing the water inputs and outputs, as illustrated in Figure 2.1.7.

Figure 2.1.7. Soil water balance in irrigated cropping systems (courtesy of Colorado State University, USA).



Irrigation and rainfall add water to the root zone. Some of this water may be lost as runoff or drainage below the root zone. Conversely, in some situations water can also enter the root zone from a high water table or lateral water movement through the soil. Water is also lost from the root zone through evapotranspiration.

The current soil moisture deficit can be calculated on a daily basis to indicate when the amount of water in the root zone is insufficient, suggesting that irrigation should be applied.

Deficit (today) = Deficit (yesterday) – irrigation – rainfall + ET_c

Where:

Deficit = soil moisture deficit (amount of available water in the root zone below field capacity)

ET_c = Crop evapotranspiration (crop water use)

Irrigation and rainfall figures have already had runoff and drainage taken into account

Note: we are using soil moisture deficit in this calculation, as that is the terminology that is most often used throughout the industry. The concept of deficit must be understood: as the deficit increases, the amount of water in the soil is less. Adding water to the soil (e.g. irrigation) reduces the deficit, bringing it closer to zero. A Deficit of zero indicates the soil cannot hold any more water.

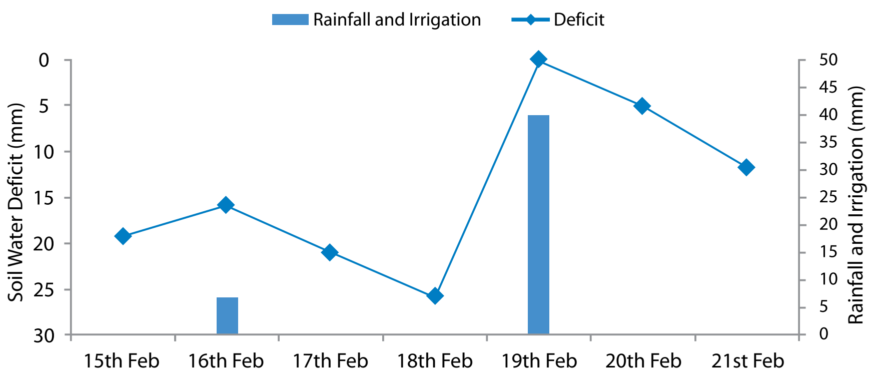
Example:

We will use the ET_c data for the soybean crop illustrated above. The items required to perform the calculations have been placed in the table below. Following the logic above:

Deficit (today) = Deficit (yesterday) – irrigation – rainfall + ET_c

or, Column 6 = Col 2 – Col 3 – Col 4 + Col 5

1	2	3	4	5	6
Date	**Deficit (yesterday) (mm)**	**Irrigation (mm)**	**Rainfall (mm)**	**Crop Water Use (ET_c) (mm)**	**Deficit (today) (mm)**
15 Feb	14			5.3	19.3
16 Feb	19.3		7	3.6	15.9
17 Feb	15.9			5.1	21
18 Feb	21			4.8	25.8
19 Feb	25.8	40		6.3	0 (–7.9)
20 Feb	0			5.1	5.1
21 Feb	5.1			6.6	11.7



In this example we can see that on most days, the soil water deficit increases due to crop water use. A small rainfall event on February 16th corresponds with a lower ET_c value, with the net effect being a slight replenishment of soil moisture. On February 19th an irrigation event takes place, with the amount applied (40mm) greater than the current soil water deficit. As the soil is full of water when the deficit is zero, additional water is lost as runoff or drainage and this amount (7.9mm) is removed from the calculation and the deficit manually set to zero.

As discussed in the previous section on Evapotranspiration, ET_c is determined from available ET_0 data by applying appropriate crop coefficients. It follows that poorly selected crop coefficients will result in inaccurate ET_c and corresponding errors in the soil water balance calculations. A recently developed tool, IrriSAT, regularly obtains NDVI (Normalised Difference Vegetation Index) data from satellite imagery (refer to WATERpak chapter 2.3).

This data can then be used to determine much more accurate crop coefficients and hence improve the accuracy of ET_c. IrriSAT uses this data to automatically calculate the soil water balance in a similar process to that described above.

Plant Based Methods

Whilst calculations of soil moisture can infer the likelihood of crop stress, direct observation of the crop can reveal the actual level of stress being experienced. Visual signs of water stress may include wilting, fruit drop and death in sections of the crop. However these signs often occur after stress has been present for some time, and are of limited use in accurate irrigation scheduling.

Furthermore, plant indicators may not necessarily be a result of water stress, but of other causes such as heat, salinity or nutritional deficiencies. For example, some plants roll their leaves up in response to an extremely hot, windy day - referred to as Midday Wilt in cotton. Other plants only show wilting when water is severely limited. These crops move into a "shut-down" phase which can impact yield depending on crop development stage at which this occurs. Other plants will wilt in response to water logging or root disease.

Whilst simple visual indicators are of restricted use for irrigation scheduling, more technologically advanced methods of plant monitoring can provide highly accurate responses to small changes in plant stress levels. In the past, these methods have often been costly and complicated, with use predominantly restricted to research.

Plant based scheduling tools can be classified as either contact or non-contact depending upon whether they have to come into physical contact with the plant.

Contact sensors typically provide point source data, with multiple sensors required wherever instrumentation is left in-situ to provide time series data. Contact sensors may be either destructive (pressure bomb) or non-destructive (sap flow, stem diameter).

Point source measurements typically record data for only a single plant; hence the way in which this plant represents the rest of the field is very important. This issue is the same for point source soil moisture measurements.

Non-contact sensors do not come into contact with the plant and usually can be used to measure numerous points across a number of fields, or even entire fields at once. Cloud cover can be a major influence as airborne and satellite sensors must be able to view the field, whilst ground level and hand held sensors usually require clear conditions to provide meaningful data.

On the whole, most plant based sensors are not yet practical for wide spread use, or do not yet offer significant advantages over other existing scheduling techniques. This may improve in the future as further research and development occurs.

Soil based methods

Measurement of soil moisture characteristics allows us to infer the likely stress that a plant may be undergoing. There are three main measurement types for determining the availability of water in the soil.

- Gravimetric – the amount of water in the soil based on weight. This is calculated by oven drying soil samples to find the difference between their wet and dry weight. This measure is of little use for scheduling due to the difference in density of different soils and the time taken to obtain measurements.
- Volumetric – the amount of water in the soil based on volume (cm^3/cm^3). This is the most common way of expressing soil moisture, usually in mm of water per depth of soil (e.g. 300mm of water per 1m of soil = 30% Soil Moisture). A number of tools use different water properties (electrical conductivity, neutron scattering) to infer the volumetric water content. A truly accurate measure requires calculation of soil bulk density.
- Soil Water Potential – measures the soil suction (pressure) and is the measure that most accurately relates to actual plant stress. The soil water potential indicates how difficult it is for a plant to remove water from the soil.

Volumetric measurements of soil moisture have become popular as they enable an irrigator to relate the volume of water required to refill the soil profile (deficit) to the amount of water applied in an irrigation event. However to achieve this with accuracy, additional information is required such as the volumetric moisture content at field capacity and refill point. This information is obtained from physical soil tests which are often time consuming to obtain. Therefore analysis of volumetric soil moisture data is often undertaken using uncalibrated data by looking at trends in daily water use.

On the other hand, measures of soil water potential can directly indicate how difficult it is for a crop to extract moisture from the soil. Thresholds of suction at which crops are able to readily extract water are generally well known, therefore a single measurement can indicate whether an irrigation is required or not. However as the information is not volumetric, determining how much water should be applied, or how long it will take to deplete the existing soil water reserves is more difficult.

A Note on Calibration:

It must be noted that neither capacitance probes nor neutron probes provide a true measure of volumetric moisture content without site specific calibration. However for general irrigation scheduling practice, accurate measurements are not required as the trend in soil water extraction and relative differences in soil moisture are sufficient. Further information is available in Chapter 2.7

Plant Based Monitoring Tools Available

Advantages	Disadvantages	Comments
Plant Based Monitoring Tool: Stem water potential *Specifications:* A pressure chamber measures the water potential of a non-transpiring leaf		
More robust than leaf water potential Relatively cheap	Destructive measurement Requires a lot of practice to make reliable measurement Point source measurement – many points required for representative sample No continuous data – new measurements Required each time.	Need more testing to determine critical levels. Research tool.
Plant Based Monitoring Tool: Canopy temperature (including thermography) *Specifications:Infra-red thermometers (IRTs) including handheld IR guns, continuous wireless fixed sensors, aerial/ground rig attached sensors and thermal imaging cameras.*		
Strong relationship between canopy temperature and plant water status, irrigation scheduling possible to maintain crop at thermal optimum (e.g. BIOTIC) Relatively cheaper wireless technology with continuous monitoring capabilities being developed Non destructive measurement Automation possible Can get a picture of whole field or many points within field Using cameras or remote sensors, many fields can be measured with a single instrument	Errors can occur if background (soil) temperatures are being measured in the field of view of the instrument Point source measurement using hand held or fixed sensors Variations in temperature depending on the part of canopy and angle of measurement Data interpretation can be difficult as both water stress and ambient conditions (air temperature, radiation, humidity, wind speed etc) influence changes in canopy temperature. Thermograph can be expensive Readings need to take ambient conditions into account Continuous measurements can result in large data sets that can be difficult to manage and interpret.	Need more testing for irrigation scheduling in Australian systems May have potential for non-point source data collection, but not yet commercially practical.
Plant Based Monitoring Tool: Leaf Water Potential *Specifications:* A pressure chamber measures the leaf water potential of a transpiring leaf.		
A classic, standard measurement Equipment relatively cheap	Destructive measurement Requires a lot of practice to make a reliable measurement. Time/conditions of day dependent for consistency over time Point source measurement No continuous data – new measurements required each time.	Research tool
Plant Based Monitoring Tool: Plant growth measurements *Specifications:* A range of plant growth technologies including stem and fruit diameter sensors		
Relatively cheap Easier for grower or consultant gives continuous data	Not accurate in all situations Additional measurements required Point source measurement - multiple sensors required	Plant growth measurements will likely provide similar function of trend analysis as current soil moisture monitoring.
Plant Based Monitoring Tool: Satellite Imagery and remote sensing of crop water stress *Specifications:* Spectral data and images of varying characteristics, resolution and coverage		
Applications are wide ranging	Accuracy is uncertain Ground truthing can be expensive	IrriSAT is a new tool which uses remotely sensed data to improve ET_c calculations. Mobile, low altitude sensors may provide a better resolution and improve application.

Source: Modified from CRC for Irrigation Futures

Soil Moisture Monitoring Tools Available

Advantages	Disadvantages	Overall
Soil Moisture Monitoring Tool: Capacitance probes – stationary (C-probe, Enviroscan, Buddy, Profile Probe, Theta Probe, ECH20, etc.) *Specifications:* **Type of sensing** – capacitance **Type of reading** – volumetric (often uncalibrated) **How does it work?** By measuring the dielectric constant of the soil. The amount of water in the soil is related to its ability to transmit electromagnetic waves or pulses		
Continuous logging Remote access Multiple access tubes to one logger Gives indication of variation in crop water use on a daily basis	10 cm diameter reading zone is reasonably small Cracking soils can effect soil moisture reading Generic calibrations give poor estimate of total water content Some models have cables from access tube to logger Unit is stationary so number of sites limited	Suitable tool for growers, be aware of issues on cracking soils. Expensive but gives detailed soil moisture record.
Soil Moisture Monitoring Tool: Neutron Probe *Specifications:* **Type of sensing** – radioactive **Type of reading** – volumetric (often uncalibrated) **How does it work?** The radioactive source emits neutrons which are slowed down by collision with hydrogen in water molecules. The number of slow returning neutrons measured is related to the amount of water in the soil		
Large reading zone (average diameter 30 cm) is beneficial in cracking soils Predictive Software Portable, multiple access tubes Usually more accurate than most other volumetric sensors	Require a license to use the probe and approved transport and storage facilities. Manual data collection Data reading of each access tube is time consuming No remote access or continuous logging Soil specific calibrations required for accurate readings Regular readings required for comprehensive date set and to identify trends. Reasonably heavy and expensive instrument. Radioactive source must be properly disposed of.	Most accurate for clay soils Need to be licensed due to radioactive hazard
Soil Moisture Monitoring Tool: Capacitance probe – portable (Diviner 2000, Gopher, Aquaterr, Profile Probe, Theta Probe, etc.) *Specifications:* **Type of sensing** – capacitance **Type of reading** – volumetric		
Quicker read than neutron probe Readout in-field Can determine change in daily water use from output graphs if readings are frequent Portable, multiple access tubes. Reasonably inexpensive	Small (10 cm diameter) reading zone Cracking soils will effect soil moisture reading Generic calibrations give poor estimate of total water content Absolute numbers obtained are of little value without calibration Frequent readings required to identify trends.	
Soil Moisture Monitoring Tool: Porous media (tensiometers, gypsum blocks, matrix sensors, etc.) *Specifications:* **Type of sensing** – pressure (suction) **Type of reading** – soil water potential **How does it work?** Porous media (gypsum, ceramic, etc) allows water to flow from soil. Pressure sensor within the device measures suction directly.		
Cheap Gives direct reading of when to irrigate Calibration is usually unnecessary Many products can be logged to provide time series data	Some products may not work well in very wet or very dry soil Does not give an indication of the volume of irrigation required Permanent installation of block devices not well suited to field crops Some products may not respond quickly to change in moisture content	Only devices to give a direct reading of how difficult it is to extract water from the soil regardless of soil type.

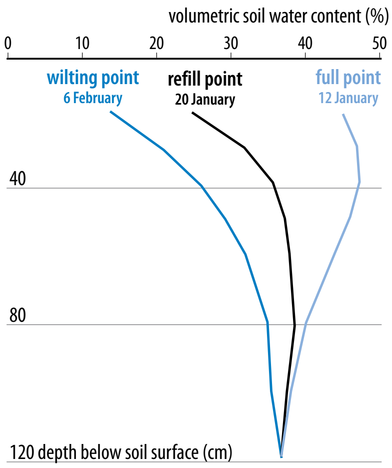
Source: RWUE3 2007

Analysing Soil Moisture Probe Data

Data from soil moisture probes will generally be presented in one of two ways::

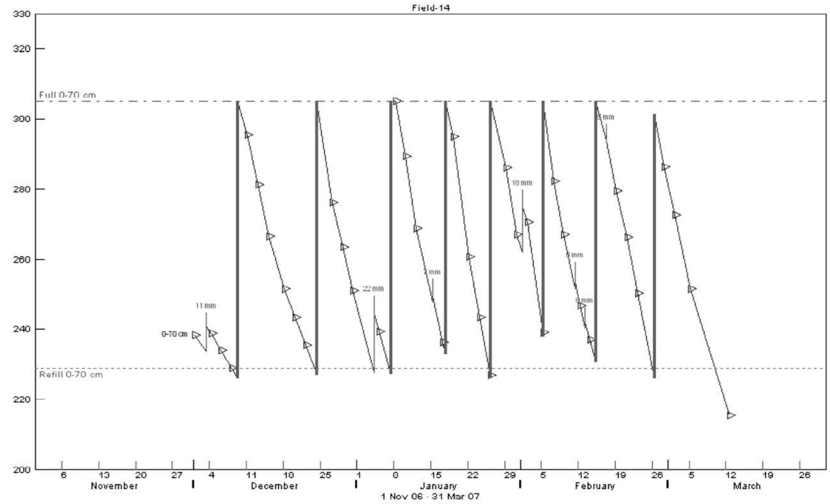
1. Non-continuous data (obtained from manual recording devices such as **Neutron probes** or **Diviners**) is often presented as a graph of soil depth vs. moisture content (Figure 2.1.8). Each line on the graph represents a reading taken at a different time.

Figure 2.1.8. Soil moisture data presentation typical of manual measurement devices (e.g. NMM)



However, data may also be represented as a graph of moisture vs. time for the total of the whole profile (Figure 2.1.9). This graph is usually most useful if readings are taken regularly.

Figure 2.1.9. Presenting non-continuous soil moisture data over time

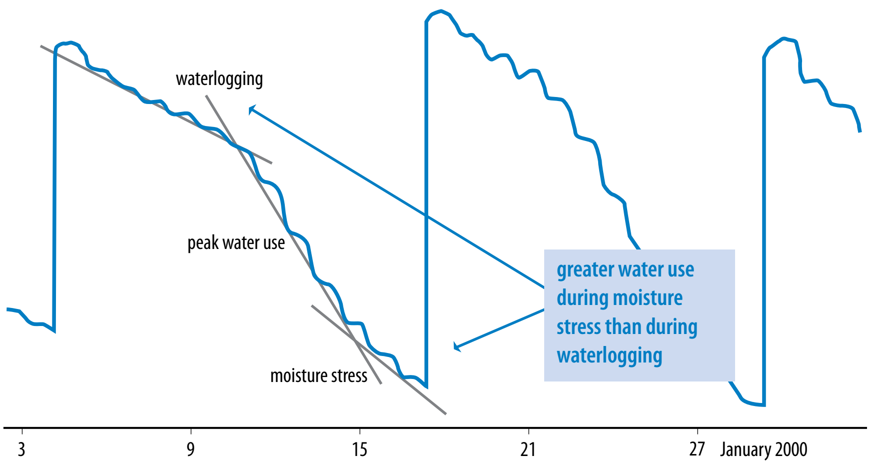


RootZone	Full	REFILL	Previous	Current	Deficit	Probe Dwu	Pdwu Date	EDWU	Date	Amount
0-70 cm	305 mm	229 mm	252 mm	216 mm	90 mm	4.9 mm/day	26 Jun	4.3 mm/day	26 06 16:20	76 mm

2. Capacitance probe data is typically presented as a graph of moisture content vs. time (Figure 2.1.10.). The line(s) on the graph can either represent a sum (total) of all soil moisture readings within the entire profile (summed graph) or each line may represent the moisture reading at a different depth in the soil profile (stacked graph).

*Note that data from either device may be presented in either fashion.

Figure 2.1.10. Soil moisture data presentation typical of continuous logging devices



Source: Sloane 2003

How to schedule an irrigation using soil moisture data

In irrigation scheduling, soil moisture data is used as a proxy for plant stress. In other words, a certain level of soil moisture deficit is chosen as the point at which the crop starts to suffer from stress due to insufficient water availability. Figure 2.1.8. demonstrated a typical presentation of non-continuous soil moisture data, but also shows the typical root extraction patterns for a cotton crop for the full, refill and wilting points. Crops will start to stress (with potential yield reduction) when they reach the refill point and will die when they reach the wilting point. Crops typically use most soil moisture in the top of the soil profile and proportionally less, deeper in the profile. Moisture is generally obtained from the top of the profile first, although on some occasions this may not occur. For example a rainfall event may cause temporary waterlogging at the soil surface whilst water extraction continues at depth.

The full point (field capacity) occurs when the soil profile is full of water and no drainage is evident. It can usually be determined by taking a soil moisture reading of the profile 1-2 days after a surface irrigation event or after a large rain event. In most cases this point is quite easily identified, particularly from continuous soil moisture data. It should be noted that although most surface irrigation events completely fill the soil profile, this is not always the case, and is almost never the case with drip or CPLM irrigation systems. In these cases, the full point may only be evident after large rainfall events.

The refill point. If an irrigation is not applied prior to soil water levels passing the refill point, then a yield reduction will occur depending on the stage of the crop. However determining the refill point with accuracy can be difficult. In part, this is because the refill point changes during the seasons. Young plants have small roots that only have access to a limited part of the soil profile. As the plant grows, the roots can access more of the profile and therefore tolerate a larger soil moisture deficit before reaching refill point. Determining an appropriate refill point using soil moisture data requires some trial and error, and is open to interpretation as no real measure of plant stress (e.g. leaf water potential) is used. The process involves examining the daily water use figures of the crop. Once the daily water use starts dropping this is a sign that the crop is experiencing difficulty getting water and the crop has reached (or passed) the refill point.

Daily crop water use will vary depending upon the weather conditions for each day (evaporative demand) as well as the difficulty with which the crop can extract moisture from the soil. Figure 2.1.10. shows how the crop daily water use can change when the plant is stressed through either waterlogging or moisture stress. When a crop reaches the refill point and moisture stress starts to occur, the daily water use declines.

Remember that uncalibrated probes do not give absolute measures of soil moisture. This means that you cannot simply take a reading of soil moisture and compare it to a refill point determined from physical soil sampling. For manual (portable) probes there are a couple of options:

- Take readings regularly (every 2 or 3 days) as well as before and after irrigations and rainfall events. This will give enough data to perform some basic trend analysis as described below.
- Use historical data. Provided you have data for a number of previous seasons, and ensuring you have enough access tubes to average out individual readings, it is possible to reduce the frequency of manual readings. Be cautious of this method where soil properties are likely to change significantly due to compaction, ripping or extended drying

Frequent manual readings or data collected using a continuous logging device can be used to deduce a refill point based upon trends in water extraction over time. As indicated in Figure 2.1.10., water extraction patterns are stepped on a daily basis, being flat at night (little or no water use) with a rapid decline during the day. The overall slope indicates how readily extraction is occurring:

- Steep slope - high water use
- Flat slope - water logging or stress

Care should be taken not to confuse a drop in daily water use caused by cloudy weather. If you have daily water use data for an entire season and want to standardize them for changes in the weather, it is possible to do this by dividing the DWU figure by either solar radiation data or air temperature data from a weather station.To schedule irrigations from soil moisture data it is important to know:

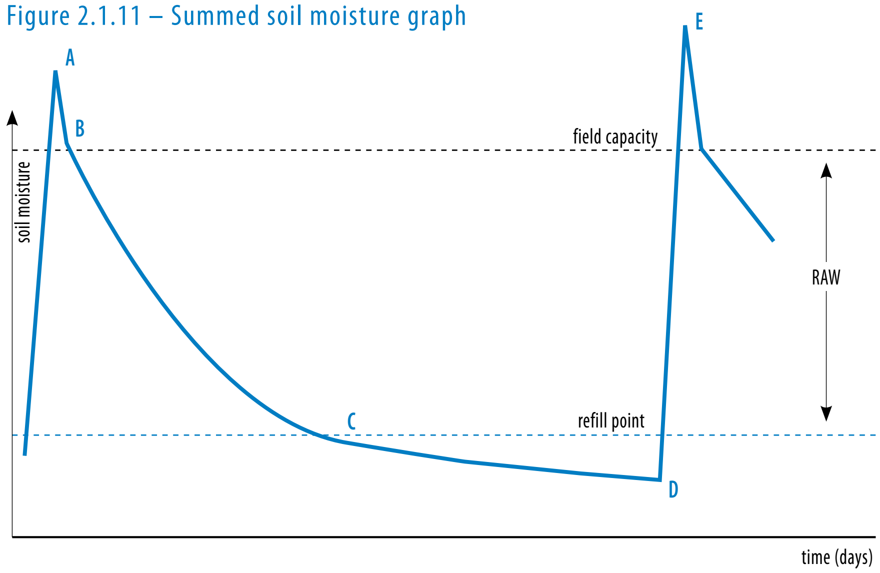
Use of the summed graph

The summed graph displays total soil moisture for the probe depth (typically 1 metre). It is useful as a 'quick reference' of soil moisture or to indicate irrigation when the refill point has already been determined. It can be used to determine field capacity (full point), but determining refill point can be more difficult because once water extraction in the summed graph has started to decline, the crop is already under stress.

Figure 2.1.11 shows a summed soil moisture graph, illustrating differences in water use over time.

- In this figure, the soil has been irrigated, becoming saturated (A).
- After irrigation ceases, soil water drains due to gravity until field capacity is reached (B). This can occur quite quickly, as illustrated here, or may take a number of days causing waterlogging (as in Figure 2.1.10).
- Under optimal conditions, the plant extracts water freely, until the refill point is reached and crop stress occurs (C).
- In this case, irrigation has been delayed and the crop has been stressed until irrigation occurs (D)

Figure 2.1.11 – Summed soil moisture graph

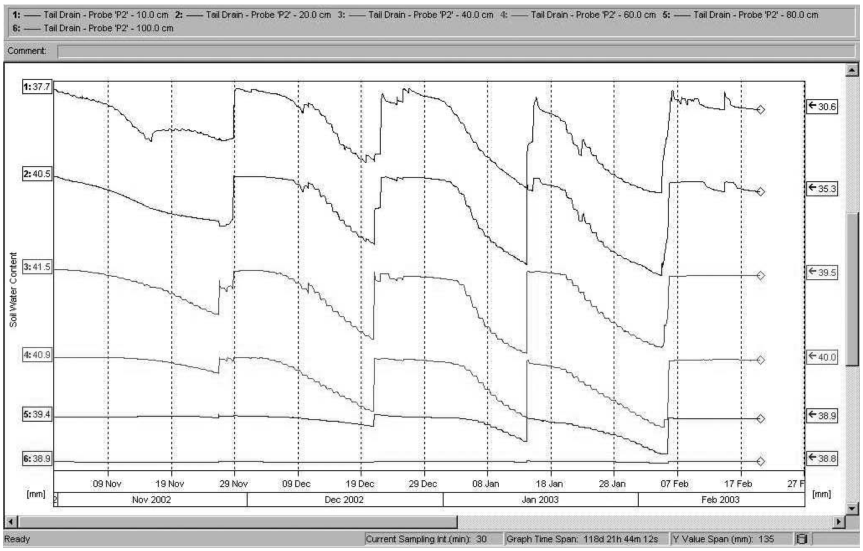


The refill point is clearly evident in this figure (at C), but by the time the decline in water use can be confirmed, water stress has started to occur. Analysing extraction patterns at different depths can help to improve the prediction of refill point.

Use of the stacked Graph

The stacked graph displays soil moisture at each sensor depth, which is useful for determining refill points and examining extraction patterns. Figure 2.1.12. shows a stacked soil moisture graph, illustrating differences in the amount of water used at different depths.

Figure 2.1.12. – Stacked soil moisture graph



A stacked graph is helpful to predict an appropriate refill point. Because a plant will typically extract water from closer to the surface first, the sensors close to the surface will show a decline in daily water use before the crop is under stress, as it is still accessing plentiful water at lower depths.

For most crops with an effective rootzone of around 1 metre, you can determine the refill point by analysing the trend of sensors at 40, 50 or 60cm, depending upon local conditions. Often a slowing of water extraction at this depth indicates that the plant is about to stress as it will have more difficulty accessing water from deeper in the profile.

It may be possible to determine when this slowing occurs through visual inspection of the graph, or the data can usually be viewed or exported so that the actual daily water use figures can be inspected. Don't forget that for an uncalibrated probe, these daily water use figures do not accurately represent the actual amount of water used by the plant in a day.

Soil Moisture Probe Placement

The correct site and installation of access tubes is critical for soil moisture monitoring tools as only a small amount of soil is sampled. Therefore, the position needs to be representative of crop type, density and vigour, soil type, irrigation system uniformity and application. Probes need to be out of the way of machinery, so they are usually placed in the centre of plant line. However in some situations, for example in skip row crops, there may be an advantage in measuring soil moisture in other locations.

A number of different techniques can be used to ensure probes are placed in a representative area of the field. Electromagnetic induction (EM) surveys can provide an estimate of soil properties such as clay content, salinity and moisture content. This data can be used in conjunction with maps of field topography, previous yield and crop vigour to determine an appropriate site for moisture probes to be placed. Further information is included in this article.

Soil compaction and its impact on setting refill points

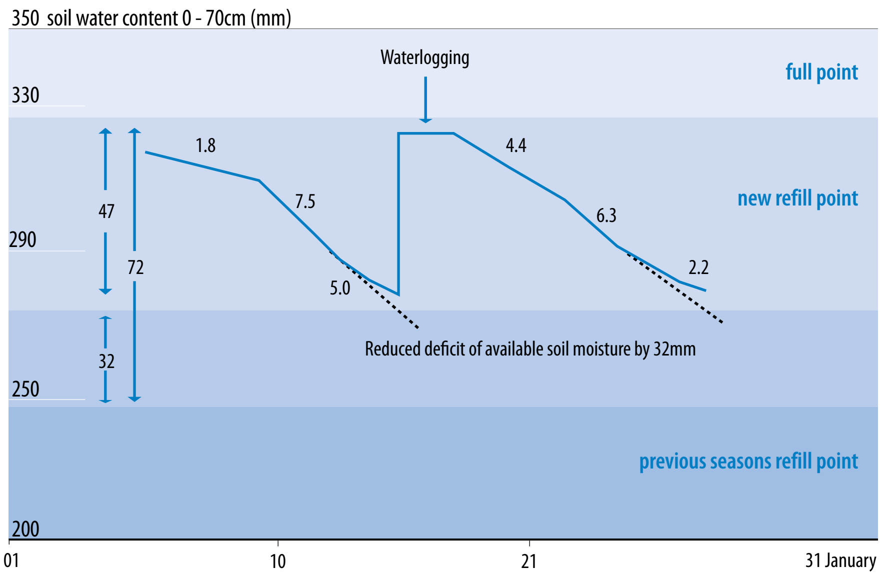
This example demonstrates how a wet pick in the previous season influences the setting of refill points the following season. A deficit of 80-90 mm is typical for heavy clay soils around Moree, which have good soil structure. Frequent soil water readings (2-3 times per week) enable the daily water use of the crop to be determined. The daily water use will decline assuming constant weather conditions, when the refill point has been reached.

Figure 2.1.13. shows, following the second crop irrigation on 2/1, a low daily water use (1.3 mm and 1.8 mm) is evident on 5/1 and 9/1 due to water logging and cool temperatures. On 11/1 the water use was 7.5 mm/day. The daily water use then dropped to 5.0 mm/day and it was decided to irrigate this crop again, at a deficit of 49 mm. This decision was based on crop symptoms and a lower than normal (7.5mm) daily water use at a deficit of 49 mm. A similar pattern of water use was evident between the third and fourth crop irrigations. Between 14/1 and 16/1 a daily water use of 0.0 mm/day was recorded due to waterlogging. This increased to 4.4 mm/day as the crop recovered from the waterlogging to a peak of 6.3 mm/day on 22/1. By 25/1 the daily water use had dropped to 2.2 mm/day at a deficit of 47 mm.

This is a similar deficit to the previous irrigation, indicating that the refill point had changed from a deficit of 79 mm which it was in the previous season to a deficit of 47 mm. Wet picking reduced the deficit by 32 mm in one season due to soil compaction (Figure 2.1.13). This reduces the interval between irrigations from about 14 days to 8 days.

Careful monitoring of the crop's daily water use and root extraction patterns as well as crop observations enables refill points to be set correctly.

Figure 2.1.13. : The effect of soil compaction on soil moisture availability



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2.2 Crop and management decisions in limited water situations

Graham Harris
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Key points

- Limited water supplies may be a result of reduced surface runoff, restricted groundwater allocations or low capacity irrigation bores and/or pumping systems
- When water is limited, profit may be maximised by adjusting cropping systems, agronomic strategies and irrigation systems and management
- There are several support tools available to assist irrigators dealing with limited water scenarios – these include Irrigation Optimiser, CropWaterUse, CottBase, HydroLOGIC and WaterSched2
- The Bureau of Meteorology also provide weather data and forecasts which can assist irrigators manage limited water availability
- No one single strategy is the best to manage limited water – usually a combination of approaches is needed

Most irrigated farms in Australian cotton growing regions are water limited, as the amount of irrigable land is greater than the typical water supply. However some farms may face additional water pressures when:

1. Low rainfall or drought conditions cause reduced surface water availability
2. Groundwater allocations are restricted, for example due to declining aquifer levels
3. Irrigation bores and/or pumping systems are of low capacity, so the available supply of irrigation water is insufficient to meet the peak demand of the crop.

Under normal water availability scenarios, most farms will practice **full irrigation**. In other words, irrigation water is applied to completely meet crop water demand or evapotranspiration (ET_c) that is not supplied by rainfall or stored soil water

However when water supplies are severely limited, irrigators and their consultants can use a number of strategies to maximise their return on the water available. These strategies relate to:

- the cropping system
- individual crop management
- the irrigation system and its management
- the farm business

Cropping System

There are several cropping system strategies that irrigators can use to manage limited water situations.

For example, reduced tillage and stubble retention, often combined with controlled traffic layouts, can result in better infiltration and use of in-crop rainfall. These techniques are increasingly favoured by growers to increase available soil water, even under conditions of typical water availability. Information on stubble retention is available at the GRDC website here and here.

Similarly, irrigators can use particular crop sequences to enhance soil water storage in fallows. An example of this can be found on the Darling Downs where a sorghum-chickpea- summer fallow- winter fallow- cotton-winter fallow to sorghum sequence has been used in response to limited water supplies. Sorghum is relatively water stress tolerant and chickpeas fix more nitrogen following the sorghum crop. Rainfall over the long-fallow provides a full profile for cotton, which is the most profitable crop in the sequence.

Reduced water availability may also lead to the consideration of alternative crops. Different crops have different seasonal ET_c requirements, and these differ between locations in response to growing season length, planting

Table 2.2.1. Average seasonal crop evapotranspiration (mm) for a range of irrigated crops.

	Narrabri			Dalby			Emerald		
Season	Dry	Average	Wet	Dry	Average	Wet	Dry	Average	Wet
Barley	383	352	332	410	387	363	420	405	375
Chickpea	424	396	364	449	419	398	292	280	260
Corn - Spring	636	598	569	599	565	548	685	659	623
Corn - Summer	624	600	564	534	529	500	605	575	537
Cotton	821	780	744	758	739	717	784	748	729
Mungbean - Spring	523	493	467	486	456	443	448	420	396
Mungbean - Summer	524	501	470	453	435	417	412	387	363
Sorghum - Spring	625	572	552	578	528	520	583	549	519
Sorghum - Summer	673	650	612	565	561	530	518	484	458
Soybean	759	726	691	671	633	622	697	657	614
Wheat	356	328	310	383	362	339	405	389	366

Source: CropWaterUse

time and weather conditions (Table 2.2.1). Therefore, the choice of crop, maturity length and planting time can be used to adjust to the limited water supply.

Crop yields generally increase linearly with crop evapotranspiration (Figure 2.2.1). Some crops (for example corn) are more responsive to every mm of ET_c than others (for example wheat). However, to achieve high yield, corn requires more water in total than wheat.

The choice between crops comes down to the profitability per mm of applied water for each crop and the total area that can be grown with the water available.

Strategies for reduced allocation

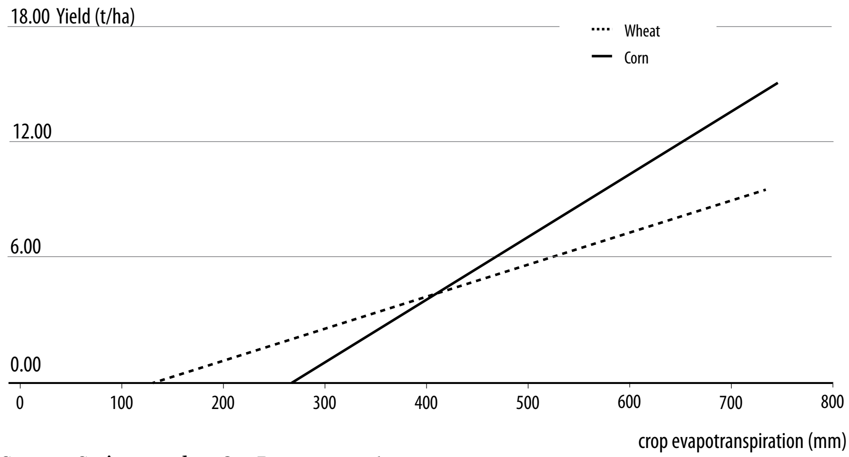
When water supply is limited growers have three management options available:

1. Fully irrigate a reduced area of irrigation
2. Deficit irrigate a larger crop area
3. Include different crops that require less irrigation

As previously mentioned, **full irrigation** occurs when irrigation water is applied to completely meet crop water demand or evapotranspiration (ET_c) that is not supplied by rainfall or stored soil water, with the typical aim of maximising yield. In contrast, **deficit irrigation** occurs when less irrigation water is applied than that required to fully satisfy ET_c. In this case, water stress occurs at some time(s) during the growing season, and irrigation applications should be timed to the most yield sensitive growth periods.

Deficit irrigation - *should not be confused with soil moisture deficit. Deficit irrigation occurs when the crop receives less water than required for ET_c. Soil moisture deficit is a measure of soil moisture status as compared to field capacity (see WATERpak Chapter 2.1).*

Figure 2.2.1. Indicative grain yield vs. ET_c relationship for corn and wheat



Source: Steiner et al, 1985; Payero, 2006.

Deficit irrigated crops will have lower yields and crop returns compared with fully irrigated crops, with the aim to maximise crop water productivity (returns per mm of applied water).

The decision to fully irrigate a reduced area minimises farm input costs and maximises the yield and return from the reduced area. The irrigator needs to know the amount of water available for the season and the likely crop water requirement. If the season turns out more favourable than expected this option can result in a lost opportunity with less total crop production than if a greater area had been planted.

The decision to reduce the supply of irrigation water to the normal cropping area runs the risk of low yields and failing to break-even if the area is not reduced sufficiently.

In reality, irrigators will choose an option somewhere between these approaches. This "best-bet" approach should be based on available seasonal forecasts (www.bom.gov.au/watl and www.longpaddock.qld.gov.au) and past experience.

Free online tools such as DAFF Queensland's CropWaterUse and Irrigation Optimiser can assist in making this decision. In addition, cotton irrigators can access the CottBase Tool through the CottASIST website (www.cottassist.cottoncrc.org.au). These tools are explained in further detail in WATERpak Chapter 2.3.

The third choice of growing different crops requiring less irrigation is often used in combination with the "best-bet" approach. For example, grain sorghum is less impacted by water stress compared to corn. It can be grown as dryland crop or with only a single irrigation applied prior to flowering. Some of the shorter-season crops are also grown when irrigation supplies are limited – for example mungbeans which use less irrigation than other summer crops because of the short growing season.

Winter crops generally use less water than summer crops due to lower evaporative demand in winter. This is one reason for including them in rotation with summer crops. Crop price and likely gross margin per ML of irrigation water should also be considered when comparing winter and summer crops.

Strategies for Low System Capacity

If irrigation system capacity is less than that required to meet crop water requirements during peak water use periods, yields will be reduced under average seasonal conditions.

Sometimes such situations can occur when irrigation systems have been poorly designed. However, low system capacity is more often due to supply constraints, such as limited bore discharge.

Management strategies for low capacity systems may aim to ensure a reasonable supply of soil moisture when peak crop water demand is experienced, for example through pre-irrigation and earlier in-crop irrigation at higher starting soil moisture levels. Then when plant demand rises above the system capacity, plants can draw on stored soil moisture to maintain yield potential.

However, with low rainfall, soil moisture levels may fall below the critical refill point during the reproductive growth stage and yields will be reduced. Similarly, if rainfall is greater than anticipated and the soil is already moist, precious rainfall may run off.

To manage this, it is possible to split irrigation fields into two or more cropping units that have different peak water needs, thus reducing the water required during both peak demand periods. This might be achieved by rotating crops to spread the irrigation season over a greater period. Similarly, staggering planting dates can offset periods of peak irrigation demand.

Crop management

Net Water Requirement

Crops use water for a range of processes including cooling, photosynthesis, cell expansion and maintaining turgor pressure. The amount of water used by a crop at any time is influenced by weather conditions, crop stage and water availability.

Furthermore, the effect of moisture stress varies between crop types and crop growth stages. Understanding crop water requirements is therefore crucial for planning your mix of crops, the area to be planted, and how irrigation is managed.

The average net crop water use by a crop (see Table 1) is the amount the crop will use in an average year, assuming soil moisture doesn't fall below critical levels. Ideally this net water requirement is reduced by effective rainfall. For example, for an average 15 October planted cotton crop at Dalby, the average net ET_C is 739mm. The average effective in-crop rainfall is 284mm. So the average net demand is 455mm (739mm-284mm).

To maximise yield, this demand has to be supplied by stored water and irrigation. If the root zone profile was full at planting (200mm of total available water) then the net irrigation required would be 255mm (455mm-200mm).

The gross irrigation requirement for a lateral move with an 85 per cent irrigation efficiency in an average year will be 300mm or 3ML/ha (255/0.85).

Similarly, the gross irrigation requirement for dry and wet seasons is 384mm and 220mm respectively (given the same assumptions).

These values can be compared with the available water to help make planting area decisions. The CropWaterUse tool can be used to make these same calculations for your particular situation.

Agronomic Practices

Agronomic practices to manage limited water scenarios differ between crop types. Detail for cotton can be found in WATERpak chapters 3.1, 3.2 and 3.3 and for other crops in WATERpak chapters 4.1 (wheat), 4.2(sorghum), 4.3(corn), 4.4(chickpeas) and 4.5(soybeans).

Choice of crop is an important consideration in managing with limited water. Some crops are more tolerant of water stress than others. It is also possible to use particular agronomic practices to manage limited water. Plant populations and row configurations have been used to manage limited water availability.

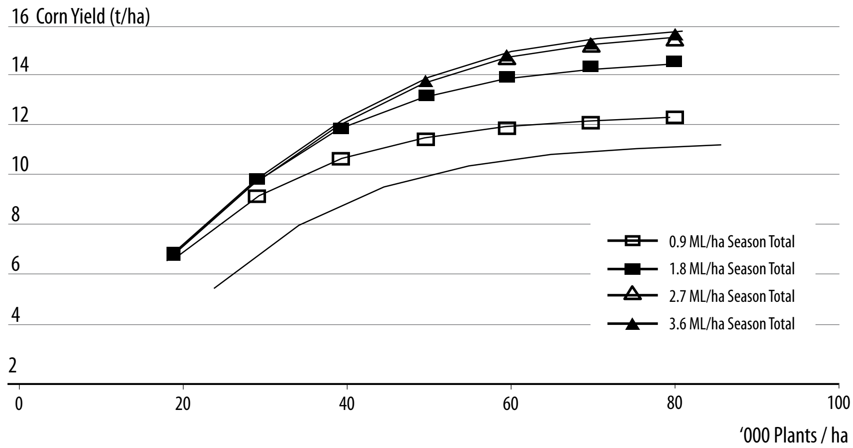
Reducing plant populations has been a strategy used by irrigators to maintain yields with limited water. For corn, fully irrigated populations are generally in the order of 55,000 to 75,000 plants per ha (the optimal established population varies with variety). For limited water situations irrigators have opted for lower populations. On the Darling Downs, consultants have recommended plant populations of 35,000 plants per ha where there is only sufficient water for one irrigation of 100 mm, and 50,000 plants per ha if two such irrigations are possible, and there is a full moisture profile at planting. Research by Peake (2008) demonstrated that optimal populations under limited water at Dalby are around 50,000 plants per ha (see Figure 2.2.2).

Plant row configurations are also used in response to limited water. In cotton and sorghum, a range of skip-row configurations have been used to maximise yield with limited water. Whilst yield potential generally declines as row spacing increases, in more favourable environments like the Darling Downs the yield penalty from single-skip configurations has been relatively minor. The reasons for using skip-row include:

- Reduced risk of crop failure
- Buy time to get rainfall or irrigations
- Spread the irrigation interval.
- Make better use of in-crop rainfall
- Reduce Bollgard II costs

Further information on row spacing in cotton crops is contained in WATERpak Chapter 3.3.

Figure 2.2.2. Corn grain yield for plant population x seasonal irrigation allocation for long-term simulation experiments at Dalby for a range of plant population densities grown on a 220 mm PAWC soil



Source: Allan Peake, 2008

Irrigation

Irrigation System

Optimising irrigation application efficiency – the amount of water delivered to the crop root zone divided by the gross irrigation water applied to a field – is important in any water limited irrigation situation. Given that ET_c is the main driver of crop yield, minimising irrigation water losses so that as much water as possible is delivered to the root zone (and therefore available to meet ET_c) is critical to maximise water productivity. Losses can occur from distribution to fields, runoff, deep drainage and evaporation.

Surface irrigation remains the dominant irrigation system within cotton-grain farming systems. Irrigators can achieve high application efficiencies with surface irrigation by:

- Shortening excessive row length
- Optimising flow rate and set times – this may include increasing furrow flow rate and cutting back on set time

These practices minimise losses from deep drainage and excessive runoff. They should be combined with tailwater return systems. Further information on surface irrigation system performance can be found in WATERpak Chapter 5.3.

Losses from distribution systems can be minimised by sealing leaking sections of channel and using fields closest to on-farm storages when water is limited.

In some circumstances, alternative irrigation systems such as overhead (centre pivot and lateral move) and drip can be used. On soils less suited to surface irrigation these systems are inherently more efficient. However, they have higher capital cost and require greater management skill.

With ringtank storages there is the potential for seepage and evaporation losses. Recent investigations have shown that the average losses from seepage are minimal. However, some individual storages may have very high seepage losses. If unsure of the losses have them assessed using a seepage meter. Seepage assessments can also provide a measure of typical evaporation losses.

Even if seepage losses are low, small errors in assumed seepage can quickly multiply into significant water volumes in seasonal water budgets. Similarly, accurate storage surveys are absolutely critical when managing small water volumes. It is not uncommon for actual storage volumes to differ by more than 20% over the design.

Once storages have been surveyed and losses have been quantified, the irrigator can decide on the most appropriate course of remediation or management, and can be sure that seasonal budgets will be accurate. Further information on storage management is included in WATERpak Chapter 1.6.

Irrigation Management

Historically pre-irrigation is used with surface irrigation in cotton-grain farming systems. Under conditions of limited water supply irrigators have opted to move away from pre-irrigation because of the high volumes of water required. Crop residue management, crop sequencing and use of fallows have been used to increase soil water storage and negate the need for pre-irrigation during extended periods of limited water availability.

Crop establishment is a distinct area of advantage of overhead (CPLM) irrigation systems, as they have the ability to establish crops with limited water and make better use of in-crop rainfall. These systems have limited the need for pre-irrigation when combined with soil water storage practices. Reduced reliance on pre-irrigation is the main reason for lower irrigation water use with these systems compared with surface irrigation (often reported to provide at least a 20 per cent water saving). This can be seasonally dependent and also depends on the efficiency of the surface system it is being compared with.

When water is limited, greater care is needed with irrigation scheduling. The aim is to supply the right amount of water at the right time. In-field soil moisture monitoring equipment used by crop consultants is invaluable in making irrigation decisions between fields and crops. This information can also be combined with decision support tools like WaterSched2 and HydroLOGIC.

WaterSched2 has been developed by DAFF Queensland to assist irrigators make real-time irrigation scheduling decisions at the farm scale. It enables irrigators to manage their available water supply and all the crops they grow on their farm at any one time. It uses local weather data and includes economic analysis to assist them to allocate a limited water resource most appropriately as weather conditions change.

HydroLOGIC is a specific cotton irrigation scheduling tool to assist irrigators manage irrigation for a single field. It combines seasonal weather data and historical data to assist cotton growers make best-bet irrigation decisions for their crop.

Irrigators can also access records and forecast information to assist their irrigation decisions from the Bureau of Meteorology. This includes:

- evapotranspiration ;
- rainfall;
- ENSO; and
- seasonal streamflow.

More information on decision support tools and data sources can be found in WATERpak Chapter 2.3

Farm Business

There are many farm business strategies that have been used by irrigators in response to ongoing limited water situations. During the Millennium Drought, strategies reported by irrigators included:

- Purchase of additional land and water.
- New technologies to minimise labour demand – overhead systems and Roundup Ready cotton varieties.
- Retaining highly skilled labour.
- Broadening income base using shares and contract harvesting.
- Growing dryland crops using water conservation strategies and use irrigation for opportunity crops.
- Careful use of forward selling for cotton.

Case Study

During the past decade, irrigators have been implementing a number of strategies to deal with limited water availability. The mix of strategies is determined by soil type, farming system, available capital and cropping alternatives. This case study is based on an actual irrigated cotton-grain farm at Dalby in Southern Queensland.

Traditionally this farm furrow irrigated solid plant cotton, corn and sorghum in a rotation outlined in Figure 2.2.3. In response to limited water, a new cropping sequence has been implemented (Figure 2.2.4). In this sequence, wheat has been added to the system and soybean has replaced the second cotton crop.

The planting rules for these two systems are outlined in Table 2.2.2.

It can be seen that available water is a critical factor in the choice between crops, and that sorghum and wheat are grown as opportunity crops depending on the occurrence of planting rainfall during the most appropriate planting window. Corn is preferred to sorghum when there is better soil moisture and on-farm water in storage.

Figure 2.2.3. Traditional crop sequence

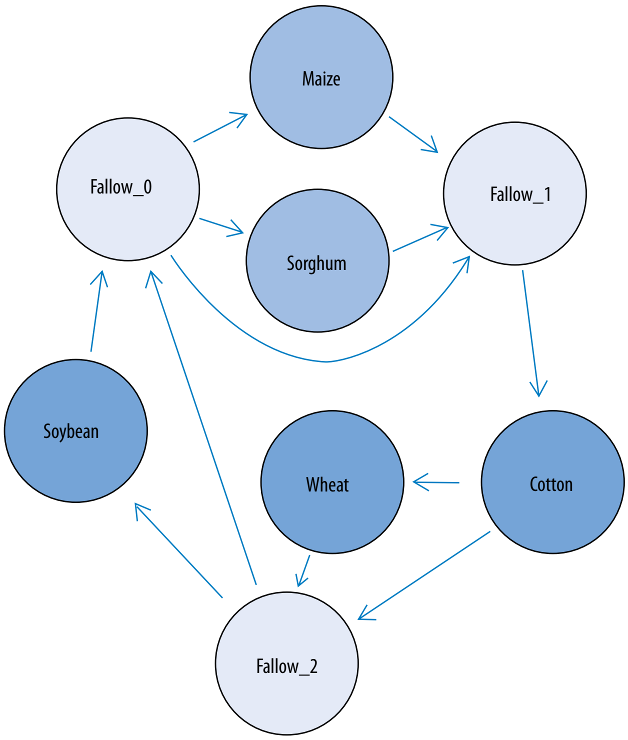


Figure 2.2.4. New crop sequence

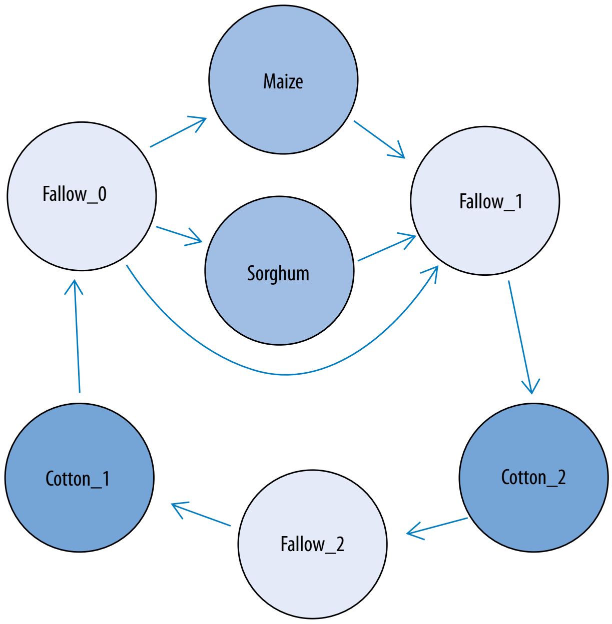


Table 2.2.2. Planting rules for each crop

Crop	Planting Dates	Available Water	Area Restriction
Corn	15 Sept to 15 Oct	≥ 4 ML/ha	410 ha
Sorghum	16 Oct to 14 Jan	≥0 ML/ha	449 ha
Cotton	16 Oct to 15 Nov	≥0 ML/ha	599 ha
Wheat	16 Apr to 1 Jul	≥ 0 ML/ha	534 ha
Soybean	1 Dec to 15 Jan	≥ 3 ML/ha	758 ha

Figure 2.2.5. Simulated applied irrigation (ML/ha) for each crop in the traditional (a) and new (b) crop rotation. The wheat crop in the new rotation is dryland.

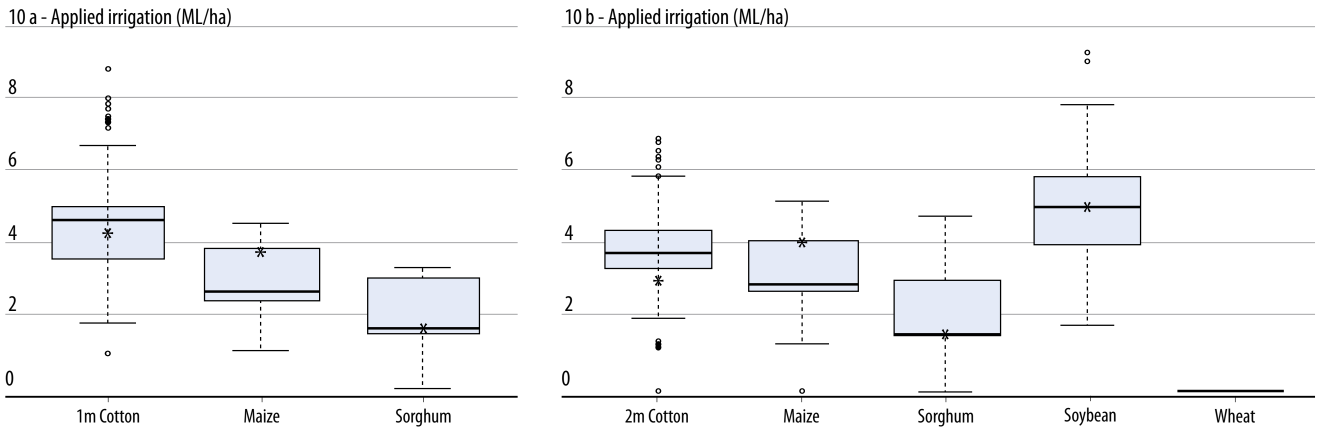


Figure 2.2.6. Simulated yields for each crop in the traditional (a) and new (b) crop rotation. The wheat crop in the new rotation is dryland.

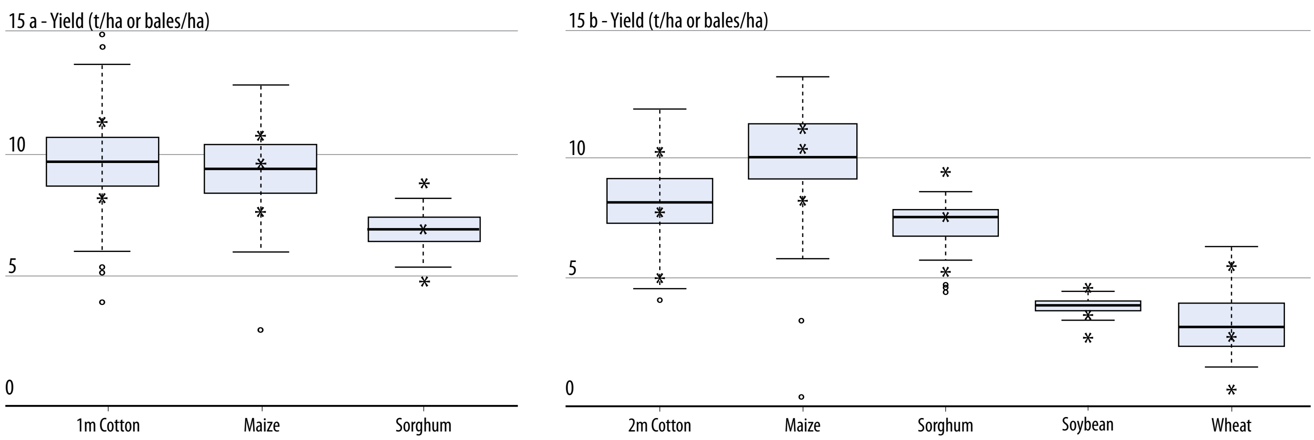


Figure 2.2.7. Simulated gross margins ($/ha) for each crop for the traditional (a) and new (b) rotations.

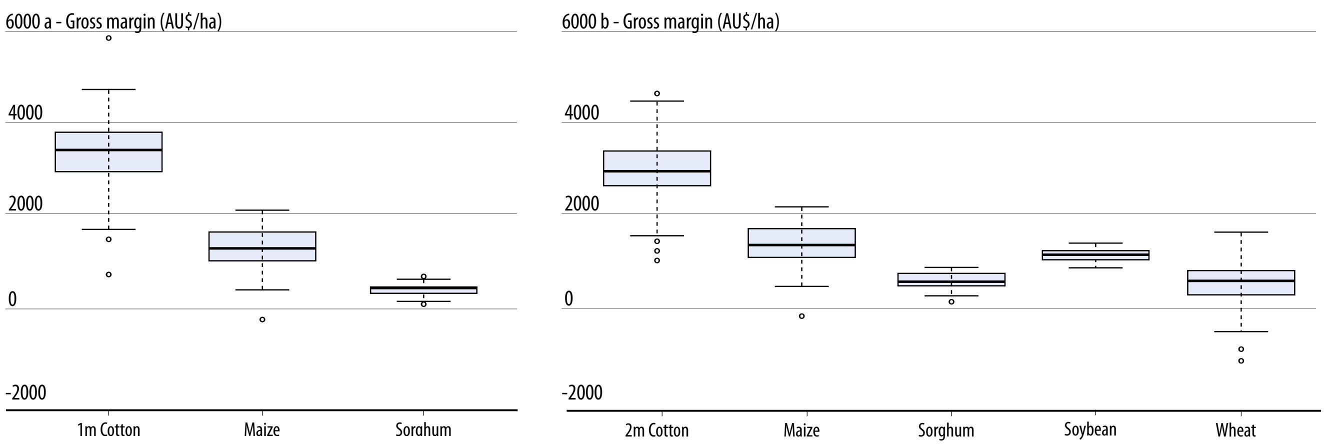
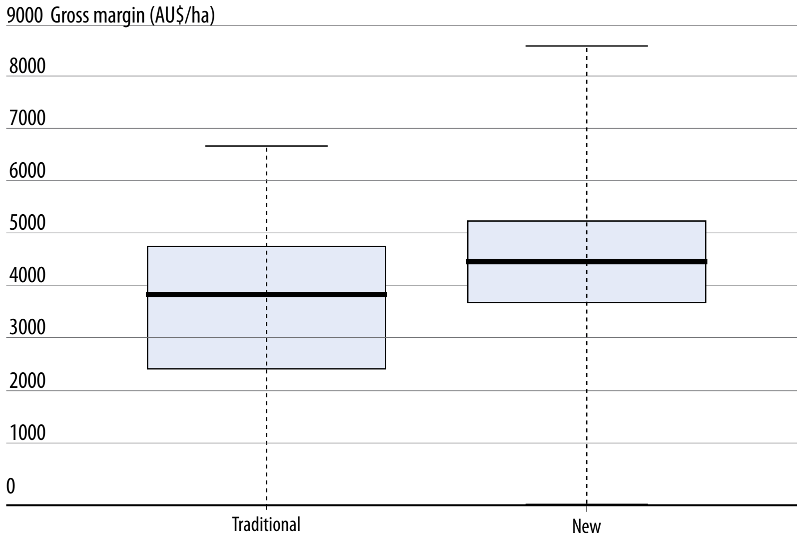


Figure 2.2.8. Simulated whole farm gross margins for the traditional and new rotations



Dryland wheat is also grown when there is planting rain after cotton – it provides a benefit in fallow by protecting the soil surface and aiding soil water infiltration.

Cotton grown in the new system is planted in a 2m row configuration (one in, one out) which uses less water than 1m cotton but limits yield potential. WATERpak Chapter 3.3 contains further information on row configurations in cotton.

APSFarm (a multi-field configuration of the APSIM model – the Agricultural Production Systems Simulator) was used to analyse the performance of the traditional and new cropping sequence for Dalby over the 119 year climate record.

This analysis revealed the following:

- The new system reduced the cotton area by 16%.
- There was a 34% increase in the area of corn.
- There was a 145% increase in the area of sorghum.
- On average 46ha of soybeans was introduced to the farming system.
- On average the new sequence increased the cropping intensity from 41% to 50%.
- 2m cotton uses less water than 1m cotton (Figure 2.2.5.), although also produces slightly less yield (Figure 2.2.6.).
- Cotton is the most profitable crop in both rotations, followed by corn and soybeans (Figure 2.2.7.).
- Wheat is the least profitable crop (Figure 2.2.7.).
- At the whole farm scale the new rotation was more profitable than the traditional system (Figure 2.2.8.). There was no increase in downside risk with the new rotation.
- The new rotation used 12% less nitrogen than the traditional rotation.

This case study demonstrates some of strategies that irrigators have used to manage with limited water. It shows that profitable outcomes can be achieved when irrigators implement these strategies.

Further Reading

GRDC 2011 Stubble Management Fact Sheet

GRDC 2011 Managing Stubble

Cotton CRC 2011 Modifying storages to save water: the cost of water saved through storage structural modifications

Cotton CRC 2011 Storages Seepage & Evaporation – Final Summary of Results

Payero, J.O., Melvin, S.R., Irmak, S. and Tarkalson, D. 2006 Yield response of corn to deficit irrigation in a semiarid climate, Agricultural Water Management 84: 101-112

Peake, A.S., Robertson, M.J. and Bidstrup, R.J. 2008 Optimising maize plant population and irrigation strategies on the Darling Downs using the APSIM crop simulation model. AJEA 48:313-325

Power, B., Rodriguez, D., deVoil, P., Harris, G. and Payero, J. 2011 A multi-field bio-economic model for irrigated grain-cotton farming systems. Field Crop Research 124: 171-179

Steiner, J.L., Smith, R.C.G., Meyer, W.S. and Adeney, J.A. 1985 Water use, foliage temperature and yield of irrigated wheat in south-eastern Australia. Australian Journal of Agricultural Research, vol. 36, pp.1-11.

2.3 Irrigation decision support tools

Lance Pendergast
DAFF Queensland

David Wigginton
DW Consulting Services

Key points

- Complex irrigation management decision making can be assisted by a number of decision support tools.
- Tools exist for a range of tasks such as scenario planning, water budgeting, irrigation scheduling and performance evaluation.
- A range of free and commercial tools that are most relevant to cotton and grain irrigators are summarised.

Growing the best irrigated crops often requires difficult and complex decision making. Thankfully, as the prevalence, flexibility and power of computing technologies and the internet have increased, so too has the range of tools designed to help irrigators source information and make management decisions.

A number of these tools have been identified in this chapter to provide an indication of what the different tools do and how they might apply to your particular situation. Because of the vast number of tools available, the descriptions in this chapter are generally quite brief, although the website links listed under each heading usually provide greater detail and may also include examples and tutorials of the tools in use.

It should be noted that technological tools such as these evolve over time and new tools can become available on a much more regular basis than can be adequately captured in a publication such as this. For this reason, readers are encouraged to search for new tools on the internet that meet your particular requirements and to refer to the specific websites listed within this chapter for the most up to date information on existing tools.

It should also be noted that the tools in this chapter have been identified because of their usefulness in irrigation management. This is by no means an exhaustive list and neither does it cover the wide range of other crop management tools that may not be specifically related to irrigation management.

CottASSIST

www.cottassist.cottoncrc.org.au

CottASSIST is a group of web tools designed to integrate the latest cotton research to assist with cotton management decisions. Developed by CSIRO Plant Industry, the Cotton Catchment Communities CRC and the Cotton Research and Development Corporation (CRDC), the CottASSIST tools include applications that can assist with irrigation scheduling, water quality and climate analysis. Whilst a summary of these irrigation related tools is included below, a number of other tools are also available on the CottASSIST website.

Day degree calculator

The Day Degree Calculator provides a measure of expected crop development based on daily minimum and maximum temperatures. These values can identify the degree of progress towards a developmental stage (e.g. first square), which is valuable information when scheduling irrigations (see WATERpak Chapter 3.2).

Crop Development Tool

The Crop Development Tool allows users to track the development of their crops and compare to known potential development rates in order to manage vegetative and reproductive growth. The Crop Development Tool is also based on the concept of day degrees and is also useful for irrigation scheduling (see WATERpak Chater 3.2) as well as the management of crop growth regulators.

Last Effective Flower Tool (LEFT)

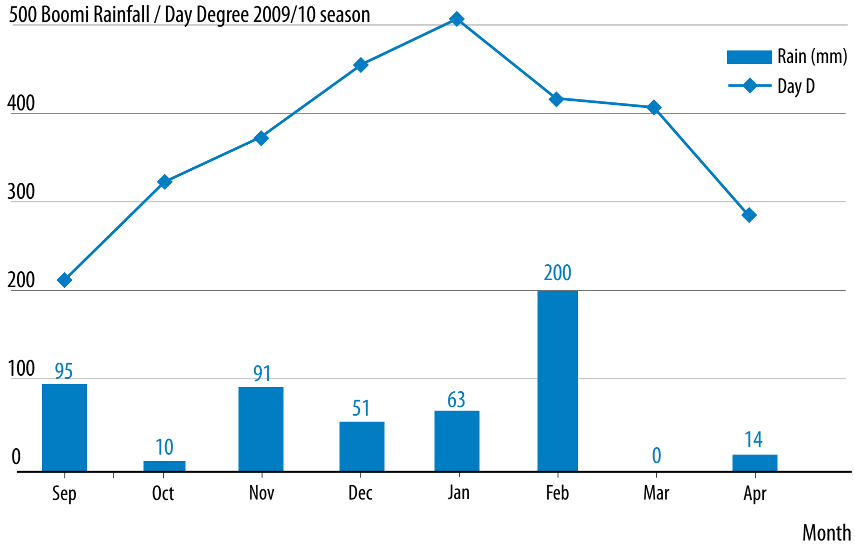
The Last Effective Flower Tool is useful for determining the target date for crop cut-out and to help schedule the last irrigation (see WATERpak Chapter 3.2). The Last Effective Flower Tool uses temperature data and day degree targets from the SILO climate service to determine the boll period (flower to open boll) and square period (square to flower) to estimate the date of the last effective flower in a season that will contribute to a harvestable boll.

Seasonal Climate Analysis

Climate variability challenges all aspects of farming in Australia and the Seasonal Climate Analysis tool can help to analyse seasonal variability or regional influences on crop performance by comparing rainfall, day degrees, number of cold and hot days with long term averages and probabilities.

The tool can be useful to obtain data for an individual season or to look at historical patterns as indicated in Figure 2.3.1.

Figure 2.3.1 - Data generated by the Seasonal Climate Analysis tool can be easily graphed.



Water Quality Calculator

For many irrigators, water quality can vary and may sometimes be poor. The use of poor quality water has the potential to impact yield and soil structure. The Water Quality Calculator helps determine the resultant water salinity (EC), Sodium Adsorption Ratio (SAR) and pH from mixing water from different sources and highlights the potential impact that this water quality may have on cotton yield.

CottBase

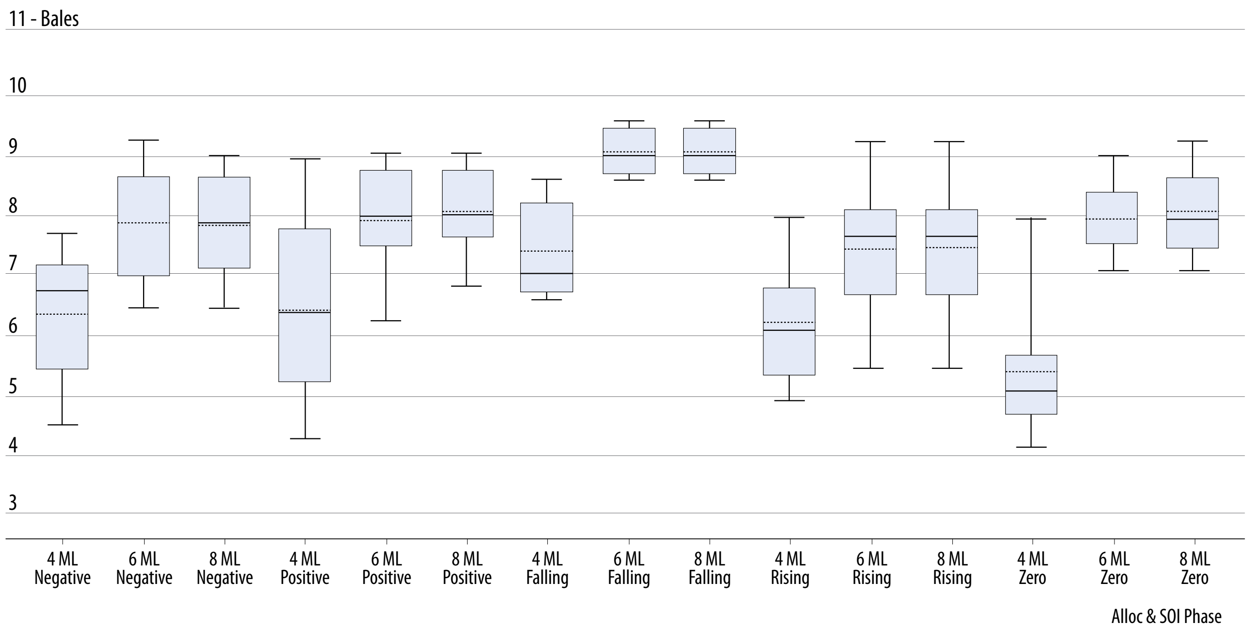
http://cottassist.cottoncrc.org.au/CottBASE/

CottBASE predicts potential crop outcomes based on crop modelling (OZCOT) and historical climate records to enable irrigators to manage risk and make improved management decisions. Variables such as plant available water content, initial soil moisture, seasonal SOI outlook, variety, sowing date, nitrogen, irrigation water availability and timing of irrigation events can be modified to make predictions for individual circumstances.

Each simulation can provide valuable data to support management decisions. For example, in WATERpak Chapters 1.2 and 3.2, CottBASE is used to predict the yield for different available irrigation water scenarios. Similarly, Figure 2.3.2 demonstrates how CottBASE can be used to investigate how the likely seasonal weather conditions (depending upon the current SOI) will impact upon yield for different amounts of available irrigation water. In this scenario, if the SOI were falling there would be less risk in allocating only 4 ML/ha of irrigation water than if the SOI were zero, where the predicted yield is lower. Such information is very valuable in determining the risks involved in different management options.

OZCOT is a cotton crop simulation model developed by CSIRO Plant Industry. The model is based on experimental research of cotton growth and development and is regularly updated with information from ongoing trials. Whilst OZCOT is not typically employed directly on-farms, it underpins a number of other tools such as CottBASE, Hydrologic, VARIWise and others.

Figure 2.3.2 – Using CottBASE to predict the effect of SOI and irrigation allocation on cotton yield.



CropWaterUse

cropwateruse.dpi.qld.gov.au

As the name suggests, the CropWaterUse tool determines seasonal crop water requirements (See WATERpak Chapter 2.1) based on historical climate data. The location, planting date and crop type can be specified to reflect a series of specific scenarios of interest. The tool will then provide reports which can show the amount of total water and irrigation required in wet, dry and average seasons, and how this varies for different planting dates or crop types.

This can be useful to help determine planting dates based on predicted water use or to determine which crop might be the best option when water is limited. Also, this data may be useful when growing unfamiliar crops where the seasonal water use for a particular location has not been experienced.

Figure 2.3.3 shows a CropWaterUse report which illustrates how the tool can be used to compare the irrigation requirements of cotton, sorghum and corn at Dalby. The number of irrigations required will be determined by the refill point the user enters into the model. A video tutorial is also available.

Figure 2.3.3 – An example CropWaterUse report showing the historical range of rainfall, water use and irrigation required for corn, sorghum and cotton crops at Dalby. More detail available from the source.

CropWaterUse

Report Compiled By:
Simon Vriesema
simon.vriesema@deedi.qld.gov.au

Summary

Project: Dalby Summer Crops
Analysis Period: *1957 to 2008*

Assumptions
RainEff: 75%   Irri.Eff: 75%   Irri.Def: 75 mm

Crop: Corn
Location: *Dalby*
Total Days: *105*
Plant Date: *01 October*
Pattern: *Dalby Early Corn*

	Init.	Dev.	Mid.	Late
Days	20	30	30	25
Kc. Val	0.4	1.2		0.5

	Minimum	Maximum	Average	Standard Deviation
Effective Rainfall (mm)	60	370	199	62
Water Use/ETc (mm)	421	573	491	33
Applied Irrigation (mm)	128	684	388	110
Number of Irrigations	1	5	3	1

Crop: Cotton
Location: *Dalby*
Total Days: *190*
Plant Date: *01 October*
Pattern: *Dalby Early Cotton*

	Init.	Dev.	Mid.	Late
Days	30	50	70	40
Kc. Val	0.4	1.25		0.5

	Minimum	Maximum	Average	Standard Deviation
Effective Rainfall (mm)	143	573	336	94
Water Use/ETc (mm)	807	1009	922	53
Applied Irrigation (mm)	315	1155	780	169
Number of Irrigations	1	11	7	2

Crop: Sorghum
Location: *Dalby*
Total Days: *130*
Plant Date: *15 December*
Pattern: *Dalby Late Sorghum*

	Init.	Dev.	Mid.	Late
Days	20	35	45	30
Kc. Val	0.4	1.2		0.5

	Minimum	Maximum	Average	Standard Deviation
Effective Rainfall (mm)	55	444	207	75
Water Use/ETc (mm)	467	633	560	38
Applied Irrigation (mm)	129	770	471	136
Number of Irrigations	2	9	6	2

Thursday, 19 November 2009   *Summary*   **Page 1 of 1**

Note that CropWaterUse uses historical weather data and is intended to predict typical water use patterns, and is not designed for use as an irrigation scheduling tool, which would require daily real-time data. However WaterSched provides irrigation scheduling functionality and is described below.

WaterSched2

http://watersched.deedi.qld.gov.au/

WaterSched2 provides irrigation scheduling and economic reporting functionality based on crop evapotranspiration. WaterSched2 achieves this by determining a daily soil moisture balance, as described in WATERpak Chapter 2.1, by taking into account daily weather, crop growth stage and irrigation applications. Actual soil moisture data can also be used by WaterSched2 to ensure the calculated soil moisture equals the actual readings.

The tool provides pre-defined crop types, varieties and soil profiles, but also allows the user to enter their own data. Similarly, real-time local weather data provided by SILO can be downloaded or users can choose to enter their own location based data. WaterSched2 can be used to manage multiple farms, fields and crops, which makes it applicable to operations of all sizes.

A range of reports are generated including irrigation date recommendations, daily soil water balance graphs, current/forecast yield estimates and seasonal report summaries. An example end of season summary report is provided in Figure 2.3.4. This report shows a number of irrigation performance benchmarks that have been calculated as well as the seasonal soil moisture balance. The soil moisture balance can be used throughout the season to determine appropriate irrigation times. A video tutorial is also available.

IrriSat

http://www.irrigateway.net/Projects/IrriSat/

IrriSat is a low cost irrigation scheduling tool which, like WaterSched2, is based on evapotranspiration data. However, where most tools that determine a soil moisture balance use a user defined crop growth pattern to determine ET_c, IrriSat uses satellite imagery to determine the actual level of crop growth. This means that the soil moisture balance more accurately represents the true conditions in each field.

The tool uses this information, along with ET data from a local weather station, to determine daily crop water use. Irrigation scheduling advice is then provided to users via SMS message on their phone or through a website interface. More information is available online along with a video describing the tool.

Water and the Land

http://www.bom.gov.au/watl/

Weather and climate information is extremely important for successful crop production. Knowledge regarding past and recent events, coupled with future predictions, helps when planning production strategies and is critical for tactical decision making. The Water and the Land website (WATL), provided by the Bureau of Meteorology (BOM), delivers a range of information that assists growers achieve this.

This website is designed to bring together a wide range of BOM services that are relevant for primary producers and natural resource managers. Different types of information are accessible from this single location and are presented in a manner that is relevant to individual circumstances.

The types of information available include:

- historical rainfall records and forecast expectations out to 8 days;
- recent and average evapotranspiration data as well as maps of monthly or annual evaporation;
- temperature information including recent temperatures, 3 month temperature outlook and frost potential;
- southern oscillation index (SOI) data and forecasts; and,
- a range of other weather and climate data.

Irrimate

www.irrimate.com.au

Irrimate™ is a commercial surface irrigation evaluation package that provides for measurement of individual surface irrigation events, evaluation of the performance of that event and determination of the combination of management parameters that would lead to optimised performance.

The service allows combinations of siphon flow rate, irrigation run time, row length and field slope to be trialled on a computer to determine their effect on performance without the cost and hassle of trialling each combination in the field. The surface irrigation performance evaluation process is outlined in some detail in WATERpak Chapter 5.3.

Figure 2.3.4 – An example end of season summary report from WaterSched2

WaterSched2

Report Compiled By:
Graham Harris
graham.harris@deedi.qld.gov.au

End of Season Summary

Field Summary

Farm:	Wallon Park	**Plant Date:**	1/09/2009
Location:	Dalby	**Season:**	2009/2010
Field Name:	Wallon Park	**Length of Season:**	147 days / 2093 GDD
Field Size:	100 ha	**Irrigation Type:**	Surface 100%
Crop:	Late Maize	**Irrigation Trigger Deficit:**	75 mm

Water Summary

	mm	ML/ha
Total Irrigation:	400	4
Total Rainfall:	149	1.49
Total Losses:	100	1
Starting Soil Water:	178	1.78
Ending Soil Water:	30	0.3
Soil Water Change:	148	1.48
Total Water Input:	697	6.97
Net Water Supply:	597	5.97

Crop Summary

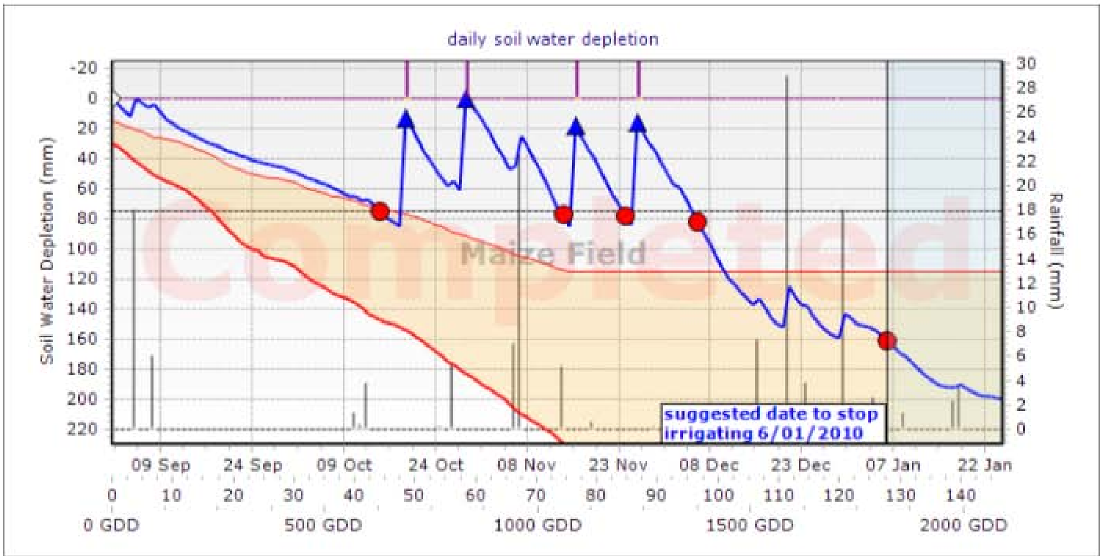
Expected Yield:	12 tonnes/ha
Predicted Yield:	10.6 tonnes/ha
Actual Yield:	10 tonnes/ha
Accumulated ETp:	657 mm
Accumulated ETc:	597 mm

Economics Summary

Price Per Unit:	$250 / tonnes
Variable Costs:	$1310 / ha
Gross Margin:	$1190 / ha

Water Use Efficiency

	Predicted	Actual	Gross Margin
Total Water Use Index TWUI	1.53 tonnes / ML	1.43 tonnes / ML	$170 / ML
Gross Production Water Use Index GPWUI	1.78 tonnes / ML	1.68 tonnes / ML	$200 / ML
Irrigation Water Use Index IWUI	2.66 tonnes / ML	2.5 tonnes / ML	$298 / ML
Crop Water Use Index CWUI	17.81 kg / mm	16.75 kg / mm	$1.99 / mm



Friday, 12 April 2013 — *End of Season Field Summary* — **Page 1 of 1**

WaterTrack

www.watertrack.com.au

WaterTrack™ is a commercial whole farm water balance tool. This allows all water on the farm to be accounted for so that sources of loss can be identified and the performance of different irrigation system components (and the whole farm) can be determined.

The WaterTrack suite of tools includes:

- WaterTrack Rapid which determines whole farm seasonal water use performance, with the minimum amount of input data required.
- WaterTrack Divider which requires some additional data but also allows losses to be segmented into different components of the farm irrigation system; storages, distribution system and fields.
- WaterTrack Optimiser which requires the most comprehensive input data but also provides detailed daily water use and loss in each individual component of the irrigation system and has prediction capability which aids in water budgeting.

The ability to accurately track water through every component of the farm irrigation system is extremely useful for optimising whole of farm irrigation management and supporting management and investment decisions. Further information and examples are available from the suppliers website provided above.

Knowledge Management System for Irrigation (KMSI)

http://kmsi.nceaprd.usq.edu.au

KMSI was developed by the National Centre for Engineering in Agriculture (NCEA) as a repository of tools designed for use by irrigators and/or consultants across a range of topics from irrigation performance to pumps and on-farm energy use. A number of the tools of most relevance to cotton and grain irrigators have been described below.

Note that some tools have open access, whilst others require registration. Some of the registered tools may be restricted to certain types of users and irrigators should enquire to see if access to the particular tool they are interested in is available.

EconCalc

EconCalc evaluate the costs and benefits associated with different irrigation system types and can be used for new systems as well as for system conversions. Economic performance indicators such as Net Present Value (NPV), internal rate of return (IRR) and Benefit Cost Ratio are calculated .

EnergyCalc

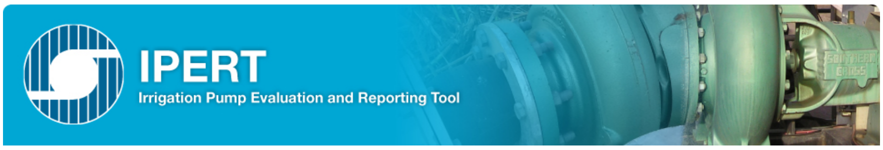
EnergyCalc can be used to assess energy use, costs and greenhouse gas emissions (GHGs) from all key on-farm processes. All energy sources are included (diesel, petrol, LPG and Electricity) so that each farming practice (tillage, spraying, irrigation, processing, etc.) can be evaluated. This can help identify potential energy cost savings and may be useful for greenhouse gas accounting. Further information is available in the online user manual.

Irrigation Performance Audit and Reporting Tool (IPART)

IPART assists in the evaluation of irrigation performance for pressurised irrigation systems (e.g. centre pivot, lateral move, drip, etc.). The tool helps to standardise the collection of infield data, calculates standard performance measures and serves as a database of performance measures so that wide scale benchmarking can be undertaken.

Registration is required to use IPART, although a public interface provides access to a summary of the performance evaluations that have been undertaken. This interface allows for basic filtering of results by irrigation system, crop type or region. This article provides a description of IPART and examples of the outputs produced.

Figure 2.3.5 – An example IPERT report showing a range of pump performance measures.



Centrifugal Electric - Report Generated From Evaluation #429 by Graham Harris on 12/04/2013

Pump

Pump		**Motor**	
Make&Type	China	Make	WEG
Model / Size	26HBO-40	Rated Output	160 kW (HP)
Nominal RPM	450	Rated RPM	1400
Measured RPM	516	Measured RPM	1400
Pump Inlet ID	750	Drive Type	V-Belt
Pump Outlet ID	559	Speed	Fixed
Suction		**Discharge**	
Inlet Pressure (kPa) (10 kPa = 1 m)	-27.69	Outlet Pressure (kPa)	21.3
Suction Line Velocity (m/sec) if measured	4.26	Nominal Discharge Pressure (kPa)	300
Suction Gauge Fitted	No	Disc. PipeID Outlet Press. Gauge (mm)	600
Suction Pipe Length (m)	3	Pipe Material	Steel
Suction Pipe ID (mm)	750	Pipe OD & Specification (mm)	660
Pipe Material	Steel	Pressure gauge fitted	Yes
Elevation Diff. b/t water source&pump (m)	-2.8	Flow Rate (L/sec)	1081
		Nominal Flow Rate (L/sec)	944
		Elevation Diff. b/t Outlet&Inlet Pressure (m)	0

Electricity Consumption

Energy Cons. over 1 hour (kWh)	100.48	Tariff Code	64
Tariff Rate (cents/kWh) (High)	31	Tariff Rate (cents/kWh) (Low)	21

Other Logged Data

There are no new sensors recorded.

Recommendation

No recommendations have been made for this evaluation

Statistics

Calculated Performance Statistics	
Flow Rate	93.4 ML/day (1081 L/sec)
Flow Rate (Target)	82.94 ML/day (960 L/sec)
Total Dynamic Head	5.74 (m)
Total Dynamic Head (Target)	30.58 (m)
Energy/Volume	25.82 (kWh/ML)
Energy/Volume/Head	4.49 (kWh/ML/m)
Performance	
Combined / Overall Efficiency	60.57%
Motor Efficiency	92%
Pump Efficiency	70.79%
Specific Speed	
Target Specific Speed	33.91
Nominal Specific Speed	33.61
Measured Specific Speed	144.58
Pumping Cost	
Peak Cost	8 ($/ML)
Comparison Cost at $0.20 kWh	5.16 ($/ML)
Off-Peak Cost	5.42 ($/ML)
Peak Cost	1.39 ($/ML/m)
Comparison Cost at $0.20 kWh	0.9 ($/ML/m)
Off-Peak Cost	0.94 ($/ML/m)

Graph

No graphs have been generated for this evaluation

Irrigation Pump Evaluation and Reporting Tool (IPERT)

IPERT is designed to assist in the evaluation of irrigation pump performance. Such evaluation is important to ensure that pumps are operating cost effectively and at the desired pressure and flow rate. IPERT standardises the data acquisition process, calculates the relevant performance measures and generates standard recommendations. Figure 2.3.5 gives an example of an IPERT report and shows a number of the performance measures that are calculated.

Irrimate Surface Irrigation Database (ISID)

The Irrimate Surface Irrigation Database (ISID) provides benchmarks of surface irrigation management and performance and enables ongoing future data collection. Data from commercial and research surface irrigation evaluations (undertaken using the Irrimate service mentioned above) are entered into ISID and the database can be interrogated by registered users to provide aggregated performance benchmarks and trends. This data has been summarised in WATERpak Chapter 1.3.

Evaporation and Seepage Economic Ready Reckoner

http://readyreckoner.nceaprd.usq.edu.au/

The Evaporation Ready Reckoner allows users to evaluate various evaporation and seepage mitigation options for on-farm storages. The Ready Reckoner determines the volume of water savings from different technologies and calculates the economic benefit of investing in these technologies so that an investment decision can be made.

As an example, the Ready Reckoner was used to evaluate storage structural changes such as cell division and increasing wall height. The results showed that such changes could often be economically justified but that individual circumstances could change the results substantially. This illustrates the value of undertaking an analysis such as that provided by the Ready Reckoner.

OVERSched

http://www.irrigationfutures.org.au/OVERsched/OverSchedv1-0.html

OVERSched is designed to assist managers of overhead (centre pivot and lateral move (CPLM)) irrigation systems. The tool is especially useful for irrigators that are new to CPLM management, because these systems require considerably different management strategies and irrigation decisions when compared to furrow irrigation.

OVERSched is not a model but a visualisation tool which allows the user to see how soil moisture might change over time. This is important for CPLM systems because soil moisture varies across CPLM fields due to the time taken for the CPLM system to traverse the field. Irrigation applications are also smaller and more frequent than for furrow irrigation fields.

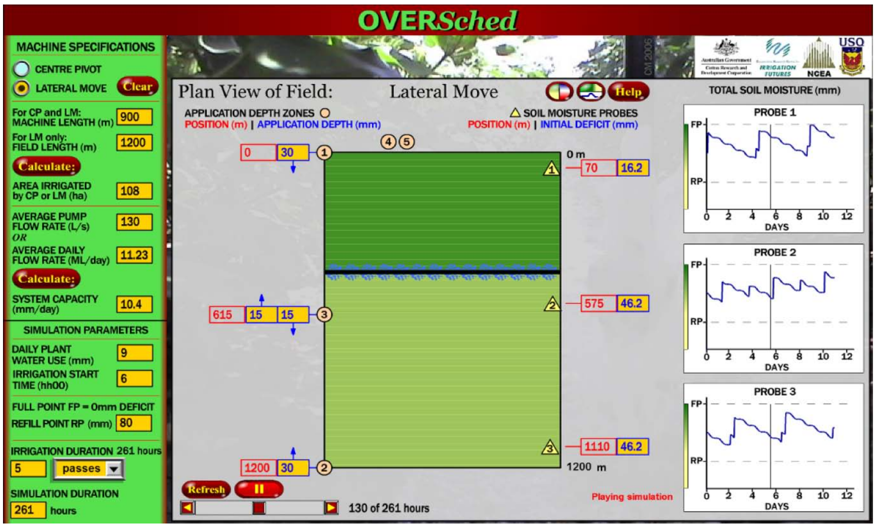
Therefore, deciding when and how much irrigation to apply following a rain event or determining the effect on soil moisture deficit at different points in the field for a range of different management strategies can be challenging and are made easier using OVERSched.

Users enter some basic machine specifications such as length and flow rate, as well as an estimate of daily plant water use. Because the tool is for visualisation only, real ET data is not used and a constant daily plant water use is assumed. It is also possible to enter the soil moisture deficit at up to three places within the field.

When entering the depth of water applied, it is possible to divide the field into a number of zones with different application depths. This is useful, for example, where a shallower application is applied under lateral moves as they approach the end of the field ready for the return run.

By evaluating the effect of different machine management strategies on soil moisture within different parts of the field, the tool can help identify the irrigation scheduling strategies that best fit your field and machine conditions and management style.

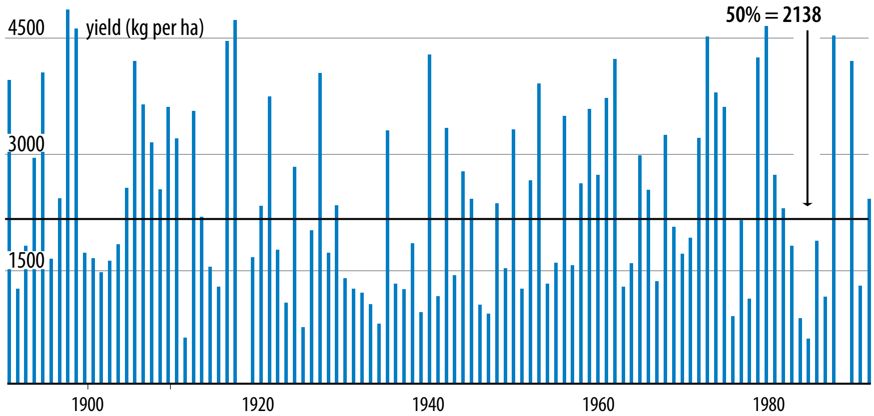
Figure 2.3.6 – An example of OVERSched showing predicted soil moisture and how this can vary over the field.



Whopper Cropper

WhopperCropper combines seasonal climate forecasting with cropping systems modelling to predict the production risk that growers face in the coming cropping season. The historical climate record is used to predict the year-to-year variability in outcomes associated with rainfed crop management options (Figure 2.3.7).

Figure 2.3.7 - Simulation results for 100 years of climate records



This helps producers to choose the best management options for the coming season. Whopper Cropper also enables price and production risk to be combined, so that the economic risk of alternative crop management options can be analysed.

Whopper Cropper enables crop management advisers to predict the likely distribution of crop yields for the upcoming season, based on starting soil conditions and knowledge of the current phase of the SOI. The Agricultural Production Systems SIMulator (APSIM) has been used to simulate a range of management options based on around 100 years of historical climate data.

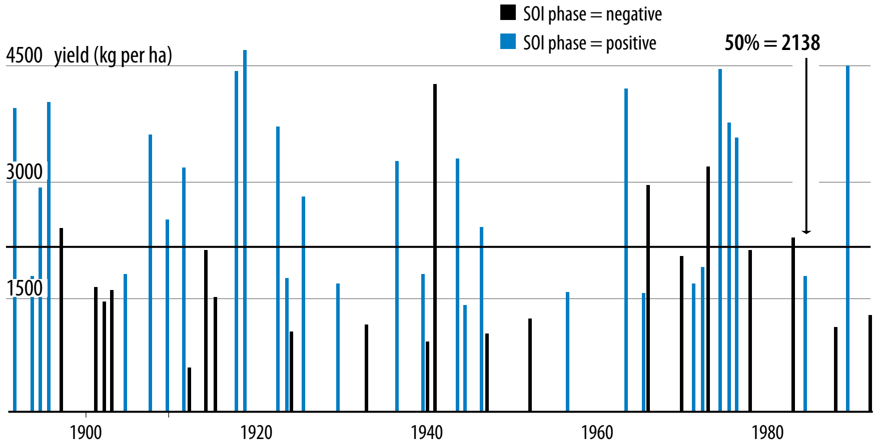
WhopperCropper contains a database of more than 600 000 pre-run APSIM simulations (currently 26 sites Clermont to Dubbo). For each site, combinations of the following options can be examined:

- 8 crops (including cotton)
- 4 soil water-holding capacities
- 3 starting soil water amounts
- 6 nitrogen fertiliser rates
- 3 crop maturities
- 5 sowing dates
- 3 row spacings
- 5 plant populations
- 2 soil fertilities
- Gross margin analysis

From this information, Whopper Cropper allows exploration of changes to management inputs that may be required under current climatic conditions. For example, the 100 year simulations of crop yields can be divided into groups of analogue years in which the SOI phase in a particular month was the same (Figure 2.3.8). Distributing simulated yields by SOI phase enables crop management advisers to discuss with farmers the best management options for the coming season.

Whopper Cropper can also determine the gross margin, which accounts for the different costs involved with different management options and also takes price into account.

Figure 2.3.8 - Analysis of simulation results using SOI phases



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2.4 Plant water status measurement

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Key points

Plant based measurements

- are effective at monitoring the water status of a crop.
- some techniques are not practical to schedule irrigations due to difficulties in accurate data collection and the requirement for some of the techniques to be undertaken on clear, sunny days at solar noon due to the high frequency of clouds at solar noon in Australia
- many techniques are useful for on-farm trials where researchers are involved.
- Developments in technology have shown potential for cost-effective plant based sensing for irrigation scheduling in Australian crops.

Plant based measurements arguably provide the most precise measure of plant water status for scheduling irrigations as they provided the integrated response of the plant to soil moisture availability and atmospheric influences. There are a range of plant sensing tools that can be used for both research and commercial crop irrigation scheduling. Satellites, airborne imaging systems and hand held instruments are frequently proposed as tools to measure crop stress caused by water, soil compaction, lack of nutrients, diseases and mites. In practice, however, there are a number of practical difficulties in using plant-based sensing for irrigation scheduling.

Many tools that in the past have only been practical for research purposes are now becoming accessible for commercial use. The development of cheap, wireless and remote sensors has renewed interest in the application of plant based sensing techniques for irrigation scheduling. This chapter briefly outlines those most commonly used plant based measurements for research purposes and irrigation scheduling. For a comprehensive review of different plant based sensing technologies see White and Raine (2008).

Plant Spectral Sensors

Plant spectral sensors operate on the principal that when electromagnetic radiation (for example light) is reflected from a surface, the properties of the surface will influence the properties (for example wavelength) of the reflected radiation. This principal can be applied to crops by looking at the reflectance from the crop canopy, which will be influenced by factors such as water stress and nutrition. Figure 2.4.1 shows the spectral reflectance of a cotton crop near Wee Waa as measured by a portable spectro-radiometer.

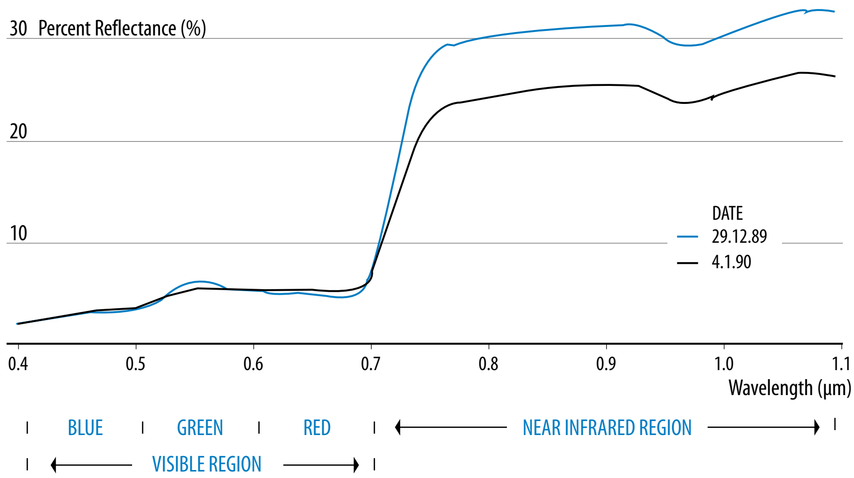
Studies have been conducted to investigate how the onset of water stress influences crop temperature and reflectance in the green, red, near infrared and thermal infrared wavelengths of the electromagnetic spectrum. These studies show that electromagnetic reflectance can be used to provide details on the spatial distribution of plant growth and development through the use of vegetation indices.

Vegetation indices are algebraic combinations of the measured canopy reflectance from different wavelength bands and are especially useful for the analysis of reflectance data. Numerous indices have been developed, most of which involve the red (0.6- 0.7 μm), near infra-red (0.7- 0.9 μm), short-wave infrared (0.8- 1.0 μm) and mid-infrared (1.0- 2.5 μm) wavelength bands.

Vegetation indices are typically the ratio of wavelengths reflected from reference and measurement surfaces (for example, leaves). One of the most commonly used vegetation indices is **normalised difference vegetation index (NDVI)**. It is calculated using the red and near infra-red wavelengths, which are the most commonly used wavelengths by remote sensing tools.

Pre-visual detection of water stress using handheld radiometers, vehicle mounted, airborne or satellite imagery to determine vegetation indices has been proposed as a more accurate way to time irrigations. Unfortunately, this is easier said than done as these instruments have so far been more successful for other applications such as measuring leaf area, detecting diseases and measuring spatial variability in fields.

Figure 2.4.1. The spectral reflectance of a cotton crop



Source: Roth 2002

Crop canopy temperatures and irrigation scheduling

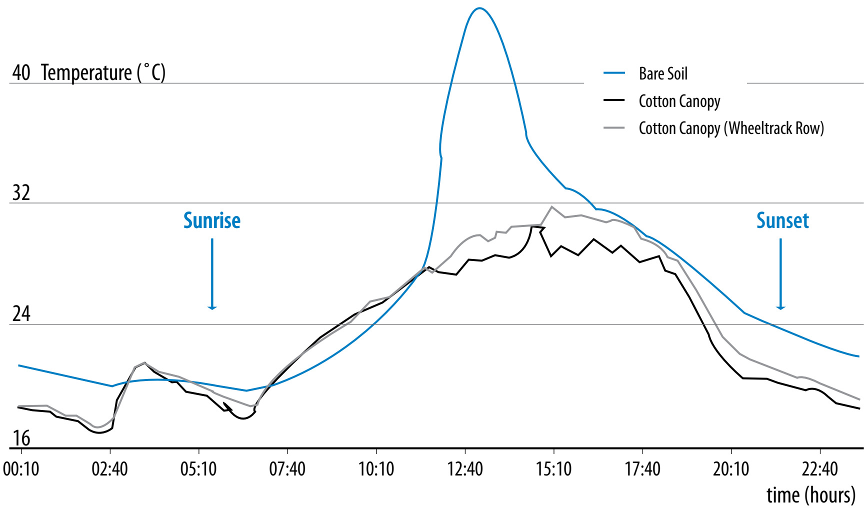
Compared to well-watered plants, water stressed plants exhibit elevated canopy temperatures. Plant leaves open their stomata to admit carbon dioxide for photosynthesis and at the same time, due to vapour pressure deficits, water vapour flows out of the leaf which cools the leaf surface. When soil water becomes limiting, transpiration decreases, thus reducing the leaf cooling effect and causing the crop temperature to rise. This occurs as a result of both reduced water availability and stomatal closure which is the plants water conservation mechanism. This is why when you touch the leaves of a well watered crop in sunlight on a hot sunny day they are cool, whereas a piece of green cardboard would feel hot.

All objects emit energy, or radiation, that is measured as their temperature. For crop canopies the temperature is usually measured with a thermal infrared thermometer (IRT). The advent of increasingly affordable and reliable IRTs and remote sensing imagery has stimulated research into plant based stress detection, through the monitoring of crop canopy temperatures.

Measurements of crop temperature can be taken using handheld or vehicle mounted devices, wireless fixed sensors, or thermal imaging cameras. Readings need to take ambient conditions into account, and errors can occur if background (soil) temperatures are being measured in the field of view of the instrument. There can be variations in temperature depending on the part of canopy being measured and the angle of measurement.

In addition, canopy temperature can vary during the day in response to both increased solar radiation and ambient temperature. Figure 2.4.2 shows the variation in canopy temperature measured by Roth (2002) over a day in a cotton crop, with differences between the temperature of the canopy measured in a compacted area (wheel-track row) compared with a non-compacted area of the crop. Data interpretation can be difficult as both water stress and ambient conditions (air temperature, radiation, humidity, wind speed etc) influence changes in canopy temperature and there are a number of approaches to interpreting canopy temperature measurements to identify crop stress to determine irrigation requirements.

Figure 2.4.2. Diurnal change in canopy temperature



Stress degree day method

Wiegand and Namken (1966) proposed that the difference between leaf temperature and air temperature (T_L-T_a) could be used for irrigation scheduling. This idea was adopted by Idso et al. (1977) and Jackson et al. (1977), who suggested the difference between canopy temperature (T_c) and air temperature (T_a) obtained about an hour after solar noon could be used for irrigation scheduling. This method is known as the "stress degree day" concept and assumes environmental factors such as vapour pressure deficit, net radiation and wind would be manifested in the canopy temperature.

The use of canopy-air differences (T_c – T_a) assumes that a well watered crop will transpire at its maxiumum potential rate, resulting in leaf temperatures lower than the air temperature and as soil water availability declines, transpiration declines and leaf temperature rises relative to air temperature. Crops with temperatures above the ambient air temperature are usually stressed.

Crop water stress index

It is known that vapour pressure deficit (a measure of humidity) and net radiation influence crop temperature. As air becomes drier the vapour pressure deficit increases and the evaporative process becomes more efficient at cooling the plant, which is similar to an evaporative cooler cooling a house.

The Crop Water Stress Index (CWSI) was proposed as a more quantitative and repeatable method for determining crop water status than the stress degree day method. The CWSI is determined by subtracting the air temperature from the crop canopy temperature and comparing the resultant value with that of a well watered crop at the same vapour pressure deficit (VPD).

The crop temperature is measured using an infra-red thermometer, while the air temperature and vapour pressure deficit are measured using dry and wet bulb thermometers, or using formulae to convert relative humidity measurements.

Idso et al. (1981) describes an empirical method for determining the CWSI while Jackson et al. (1981) gives a theoretical explanation of the index. The CWSI value is a measurement of the reduction in transpiration, expressed as a decimal in CWSI units. The CWSI has values ranging from 0 (no stress) up to 1 (maximum stress). A CWSI value between 0.25 - 0.35 would occur when the irrigation is due.

The CWSI is characterized by a lower limit or a "non-water stress baseline", at which the plant is experiencing no stress, and an upper limit where the plant is experiencing severe stress.

Idso (1982) defined non-water-stressed baseline for 26 different species for clear sky conditions and found that these baselines were different for various phenological stages in certain crops. For winter wheat crop, different baselines should be developed for pre and post head stages. Gardner et al. (1992) suggested that baselines are strongly location dependent, and perhaps species and variety dependent.

To determine a non water stressed base line it is a matter of measuring a non stressed crop canopy temperature over a range of VPDs. This can be done by monitoring it as it changes over one day or by taking measurements on different days when the VPD is different around solar noon.

The CWSI is calculated by using the following formula: Where

A is the upper limit of $T_{crop} - T_{air}$,

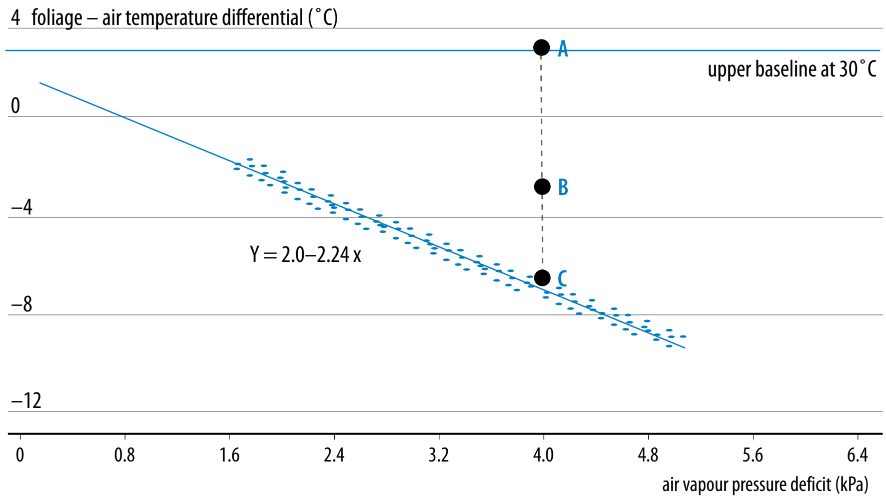
B is the actual measured vale of $T_{crop} - T_{air}$ and

C is value of $T_{crop} - T_{air}$ if the crop were non-stressed (Figure 2.4.3).

$$CWSI = \frac{B - C}{A - C}$$

While in theory this method is very sound and has worked well in irrigation experiments in dry, sunny climates like Arizona, it has not been adopted in Australia. It is more difficult to get baseline data in Australia as the climate is more humid and the VPD range is much less. Furthermore, measurements are required to be taken at peak daily radiation (normally between 12 and 2 pm) on clear cloudless days. Patchy clouds can often build up after midday in Australia and create problems when applying plant based measurement techniques for irrigation scheduling. These combined factors make it is more difficult to collect the data on a routine basis. However, the major limitation to the use of thermal sensing in the past has been the requirement for repeated measurements and the importance of adhering to specific sampling times to calculate the CWSI accurately.

Figure 2.4.3. Theoretical relationship between the canopy air-temperature difference and the vapour-pressure deficit



Relative temperature differences

Canopy temperature variations due to stress are only small (1-3°C) and difficult to separate from variations caused by diurnal and daily changes in radiation. An alternative way to use crop temperatures for irrigation scheduling is, on any one day, to measure the canopy temperature of a well watered crop and use that as a base temperature to compare with other crops on the same day.

Crops with warmer temperatures are likely to be more stressed. Thus, water stress can be assessed by examining differences in canopy temperature between the field in question and a well watered area of the same crop in the near vicinity. This assumes environmental effects are common to all areas on a farm at the measurement time.

Another option, for those growers interested in precision water management techniques, is to use a cropped field as its own reference point and examine the temperature variability within the field.

BIOTIC – Biologically Identified Optimal Temperature Interactive Console

BIOTIC is an irrigation scheduling tool developed in the U.S.A, based on canopy temperature using a temperature-time humidity threshold system (Upchurch et al., 1996). BIOTIC differs from other temperature-based irrigation scheduling methods as it compares canopy temperature with a biologically based estimate of the optimum temperature of the plant using a three step threshold system.

The first threshold is the species-specific optimum temperature. This optimum temperature or threshold temperature is based on the observation of the thermal dependence of plant metabolic activity and represents the plant's ideal temperature for metabolic and enzymatic function.

The second threshold is a time threshold. This time threshold represents the amount of time that the temperature of a well-watered crop canopy can exceed the temperature threshold, regardless of plant available soil water capacity. This is important, especially in irrigation systems where irrigation cannot be applied at short intervals and large soil water deficits are inevitable.

The final threshold is a limiting relative humidity threshold. The relative humidity threshold is important as under certain environmental conditions, relative humidity can limit transpirational cooling to the point that canopy temperature may exceed the optimum, regardless of soil water. Therefore, temperatures above the optimum under these conditions are not considered in the irrigation scheduling decision-making process.

Under the BIOTIC irrigation scheduling protocol, irrigation is considered appropriate when canopy temperature exceeds the threshold temperature for a period of time in excess of the time threshold when relative humidity is not limiting transpirational cooling (Mahan et al., 2005).

The primary advantage of BIOTIC is that it utilises a plant based biological basis for scheduling irrigation, its simplicity and provision of reliable irrigation scheduling (Mahan et al., 2000). It does not provide information on the amount of water applied in response to an irrigation signal and is designed to provide full irrigation. It can provide irrigation signals at any frequency, however as the interval between detection of water stress and the irrigation event increases, the irrigation signal becomes increasingly complex (Mahan et al., 2000). This is especially important in the context of evaluating the utility and adaptability of BIOTIC to large deficit irrigation scheduling systems such as furrow irrigation.

This system utilises wireless infrared thermometers (IRTs) that continuously measure canopy temperature overcoming many of the limitations in measuring canopy temperature using hand-held IRTs.

The existing thermal optimum approach to irrigation scheduling, BIOTIC, is limited in that it is designed for precision, low volume irrigation application systems. Therefore in its original form, BIOTIC has not been implemented in furrow irrigation systems where large soil moisture deficits occur. Recent research by Warren Conaty (2010) in Australia has identified that this system could be adapted to suit irrigation systems with large soil moisture deficits and is a subject of current research.

Airborne Thermal Infrared Imagery

It is possible to "photograph" the crop temperature to examine the spatial variation of crop health within and between fields on farms. This can be done from an aircraft or satellite. Problems with satellite imagery in the thermal infrared band include: poor spatial resolution (120 metre pixels), image capture at the wrong time of day (early in the morning – 10.00am, which is not good for stress detection) and the frequency of satellite passes creates problems obtaining images. Airborne imagery can be collected any time and is usually done about 6000-9000 ft above ground level, which results in a pixel resolution of about 3 metres.

In addition to scheduling irrigations, thermal imaging has other potential applications including:

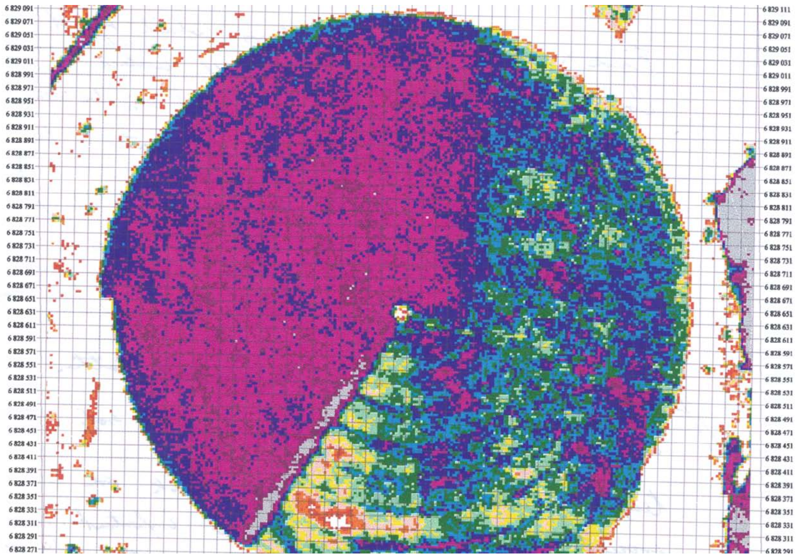
- growers and consultant knowledge of the variability in their fields
- detecting low spots and water logging problems
- early "cut out" detection of highly loaded crops
- early detection of fusarium wilt disease,
- insect monitoring such as mite hotspots, high LAI, etc
- accurate potential yield variation maps
- defoliation information with rank and late maturing crop areas identified for variable rate and product selection,
- hail damage assessment,
- agronomist overview and precision mapping overlay with EM surveys,
- farm maps.
- examination of drip and spray irrigation system distribution.

Figure 2.4.3 shows a well watered cotton crop (28°C – crimson). The higher the temperature, the more stressed the crop, and this is shown by yellow/orange colours.

- The highest crop temperatures between 6 and 7 o'clock are around 31°C (yellow/orange).
- Crimson colours indicate cool crop temperatures and well-watered conditions
- The centre pivot itself can be seen at seven o'clock (grey colour), as the water is the coolest part of the pivot.

An important feature evident in this image is the greater spatial variation in a crop's temperatures as it approaches an irrigation. This image also shows the GPS coordinates which allows any problem points to be accurately located.

Figure 2.4.4. Airborne thermal infrared image of a cotton crop



Relative Water Content

Relative Water Content (RWC) estimates the water content of sampled leaf tissue relative to the maximum water content it can hold at full turgidity. It is a measure of water deficit in the leaf. It is only used for research purposes with samples processed in controlled conditions. Normal values of RWC range between 98% in turgid and transpiring leaves to about 40% in severely desiccated and dying leaves. In most crop species the typical RWC at about wilting is around 60% to 70%.

Discs are cut from the leaves, to obtain about 5-10 cm^2/sample, for no more than two hours at and after solar noon. Each sample is placed in a pre-weighed airtight container and kept cool until it reaches the lab. In the lab containers are weighed to obtain leaf sample weight (W), after which the sample is immediately hydrated by floating on de-ionized water to full turgidity under normal room light and temperature. After 4 hours the samples are taken out of water and dried of any surface moisture and immediately weighed to obtain fully turgid weight (TW). Samples are then oven dried at 800°C for 24h and weighed to determine dry weight (DW).

$$RWC\ (\%) = [(W - DW) \div (TW - DW)] \times 100$$

Where, W = sample fresh weight, TW = sample turgid weight, DW = sample dry weight.

Pressure Chamber (Pressure Bomb)

The pressure chamber technique for measuring plant water potential has been a standard research technique since the 1960's. It was tried in the Australian cotton industry in the early days, but is no longer used for commercial irrigation scheduling because of problems getting repeatable data due to cloudy weather. It is still used in countries that do not experience clouds such as Israel and California.

Stem parts, leaves, branches or whole plants are placed into the chamber so the cut end protrudes through the specimen holder. Pressure (nitrogen) is applied to the plant part until a drop of sap is observed at the cut end. The pressure required to force a drop of sap from the sample is equivalent to the force with which water is held to plant tissues by forces of adsorption and capillarity. In order to use the pressure bomb as a tool for irrigation scheduling, pressure bomb data have to be correlated with soil water potential data (using a neutron moisture meter and potential evapotranspiration). With this relationship, it is possible to characterize the irrigation scheduling for a specific crop.

Sampling should be done under full sunlight that is cloud free. Under milder or cloudy conditions readings will be less negative and won't give a useful indication of soil moisture. Daytime/solar noon measurements are difficult to interpret and some researchers like to examine pre dawn data to see whether plants are completely recovering from moisture stress overnight. Sampling is easy and generally the uppermost fully expanded leaf petiole is used.

Delays between petiole removal and measurement can introduce serious errors in the readings obtained due to moisture loss before measurement. The best method is to take the readings in the field. Moisture loss can be minimised by wrapping the leaf in clear plastic 'cling wrap' before excision and placing the leaf still wrapped into the chamber for measurement. Much more consistent results are obtained this way. Some level of experience is required for repeatable results, and the operation of high pressure equipment is potentially dangerous, however maintenance of pressure chambers is minimal and they are simple to operate.

Thermocouple Psychrometer

Measuring water potential by thermocouple psychometry refers to the measurements of the difference in temperature between an atmosphere and a freely evaporating moist surface. In that atmosphere the psychometer measures small differences in vapour pressure. A thermocouple is formed where wires of two different metals are joined.

If the two junctions are held at different temperatures, an electric current will flow through the circuit. The magnitude of the current is a measure of the difference in temperature between the two junctions. Thermocouple psychometry depends on the principle that water vapour at equilibrium with plant tissue will have the same water potential as the tissue. Water potential of tissue can be measured by measuring the vapour pressure of the chamber in which plant material is sealed.

The plant material is sealed in a small chamber with a thermocouple junction and a drop of water. The chamber quickly saturates with water vapour. Since the water potential of the tissue is more negative than the water potential of the pure drop of water, water vapour moves from the drop into the tissue. As the water evaporates from the junction, the temperature drops. This drop in temperature is compared to a known ambient temperature and vapour pressure calculated.

Porometer

The loss of water (evaporation) by plant leaves is regulated by the stomata (pores) of the leaves, as absorption of CO_2 takes place for photosynthesis. It is an important indicator for the physiological condition of the plant. The opening of the stomata can be interpreted as the resistance against gas diffusion and is measured using the porometer. Measurements of diffusion conductance are therefore important indicators of plant water status and provide a valuable insight into plant growth and adaptation to environmental variables.

Sap flow sensors

There are three types of sap flow sensors: heat balance, heat pulse and thermal diffusion. The heat balance sensor is placed around the stem and the others require probes to be inserted into the plant stems. These sensors measure the velocity of sap flow by monitoring changes in sap temperature when heat is applied to the stem. The resulting measurements can be related to plant water status as transpiration induces sap flow. These instruments have been mainly restricted to scientific investigations.

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2.5 Managing soils for irrigation

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Key points

- Farm management affects soil structure, which in turn affects plant available water.
- Good soil structure is essential in maximising water use efficiency.
- Soil pit observations, chemical testing and visual inspection will help soil management decisions.
- Irrigation system construction efficiency will be influenced by soil type.

Soil water availability depends on a number of soil properties, including texture and structure.

Soil texture is determined by the particle sizes that a soil is made up of. The proportion and type of the smallest particle, clay, is most important in determining how the soil behaves. Different clays and the cations found within clays affect:

- nutrient-holding capacity
- the capacity of the soil to regenerate, and
- the likelihood of soil problems when subjected to application of water.

Texture and clay type also influence how much of the irrigation water applied to a soil can be stored for use by the plant (Table 2.5.1).

A thorough introduction to soil water is included in WATERpak Chapter 2.1.

Steps for determining plant available water content are well covered in SOILpak and therefore are not repeated here.

Table 2.5.1. Soil type and amount of water available to plants between field capacity and permanent wilting point for well-structured soil (top metre)

Soil type	Plant available water capacity (mm)
Sand	70
Sandy loam	140
Clay loam	140
Heavy clay	150
Well structured clay	200

Source: *Irrigation scheduling of cotton*, CRC information sheet

Soil structure, which is strongly affected by farm management, further influences the amount of water available to plants. The history of tillage, compaction, wetting and drying, plant growth and soil biology and chemistry influence soil structure.

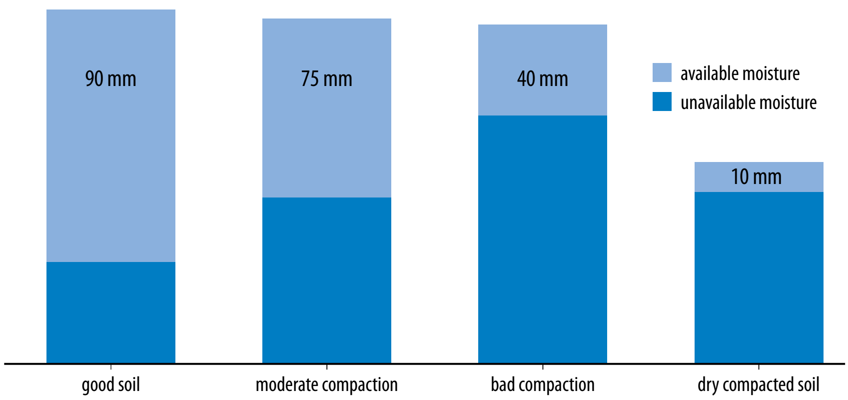
Pores, compaction and plant available water

An interconnected network of macropores is required for good water and oxygen entry to the depth of the root zone.

Disruption to the interconnectivity of pores and reduction of the total pore space by compaction from farm implements and dispersion in unstable soils affects the amount of water that is available to plants between irrigation events.

Compaction is more about loss of root pathways than lowered soil water storage. This is why a compacted soil shows only a small decrease in the total amount of water actually stored in the profile when measured with a sensing probe, but water available to plants is much reduced (Figure 2.5.1).

Figure 2.5.1. Changes to plant available moisture with compaction (cracking clay example, top 60 cm)

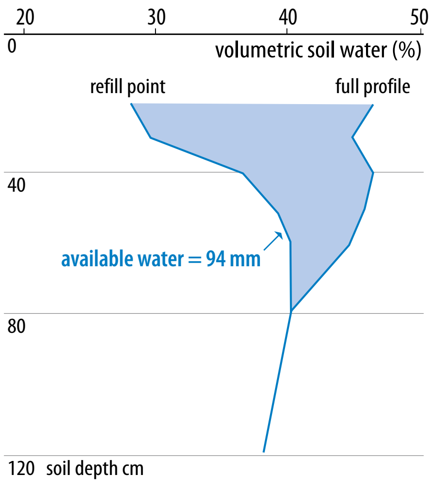


Source: from *Cotton production during drought* 1995

Normally roots follow the path of least resistance when exploring the soil for nutrients or water — the path generally follows natural crack lines, especially in cracking clay soils or biopores (old root channels, faunal tunnels, and so on). As soil compaction increases, there are fewer pores, and roots have to push through soil where pores have been destroyed. There is a maximum force that roots can exert on a soil, and as the soil dries and its strength increases it becomes impermeable to roots. If the soil is well structured with numerous pores, plant roots can still explore a large area of soil by following these cracks or pores.

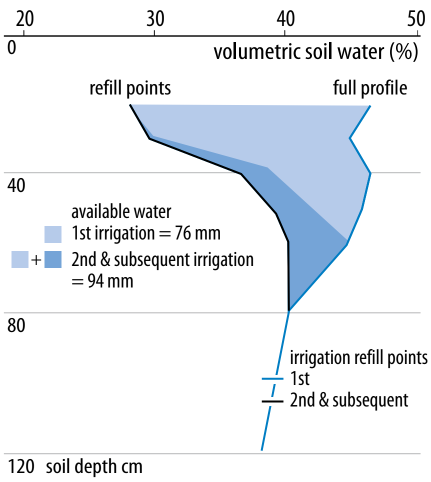
The next three diagrams (Figures 2.5.2, 2.5.3 and 2.5.4) from the SOILpak manual show patterns of water extraction from a well- structured cracking clay soil, a soil with a moderately compacted layer and a heavily compacted soil. Note that the availability of water within the profile can change between irrigation events. As the soil is wet, strength decreases, and there is opportunity for roots to penetrate compacted zones: the extent to which they do this is related to the degree of compaction. Heavily compacted soils may show marginal increases in extraction between each irrigation event.

Figure 2.5.2. Well-structured soil, extraction pattern



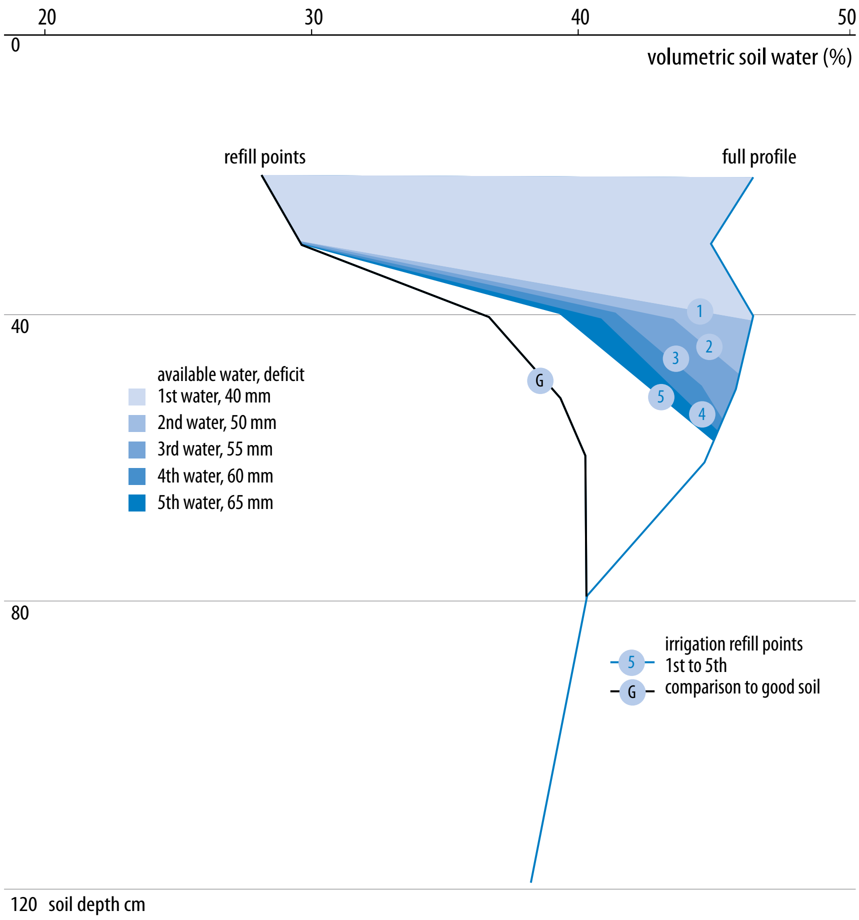
The soil water profiles in Figure 2.5.2 show typical extraction pattern from a well-structured soil. The soil is able to provide the plant with 94 mm of water. Extraction has taken place down to 80 cm. The right-hand line is the amount of water in the profile after irrigation, the line on the left being the amount in the soil when the plants are starting to show signs of requiring water.

Figure 2.5.3 Moderately compacted soil, extraction pattern



This profile in Figure 2.5.3 shows what can happen in a soil that has a light compaction layer that roots are able to penetrate after the first irrigation. The plants before first irrigation are showing stress at a water deficit of 76 mm, with water extraction only to 60 cm depth. Following the irrigation, the plants begin to extract water beyond 60 cm to a deficit of 94 mm, indicating that the roots have penetrated a compaction zone.

Figure 2.5.4 Heavily compacted soil, extraction pattern



The profile in Figure 2.5.4 shows what may happen with severe compaction. The diagram shows 5 subsequent refill points as the season progresses. Following each irrigation, the crop is able to utilise more water as it penetrates the compaction zone, however the crop is never able to extract as much as a crop on a well-structured soil (the G line).

Managing the soil environment

Do I have a soil problem that needs to be addressed?

Simple soil observations can be made to determine if you have soil structural problems. The manual *SOILpak for cotton growers* is a valuable source of information on what to look for in soils if you suspect a problem. Part C of the SOILpak manual ('Diagnosing soil condition') outlines simple methods of diagnosis.

Major problems that interact with irrigation include:

Compaction

- A problem common to all soil types in the Australian cotton industry. Over recent years the use of permanent beds and minimum tillage systems has lowered the incidence of this problem, but wet harvests and movements in plant beds with time can reintroduce the problem.
- Cracking clay soils are particularly vulnerable to compaction damage if trafficked when the soil is moist. If traffic has occurred under these conditions, observations should be made to determine the extent of damage and whether remedial measures are needed.
- Compaction can be managed, and, if confined to limited areas away from the water infiltration and rooting zone, its effects can be minimised.
- Use a visual inspection using a spade or backhoe pit to determine if a problem exists.

Sodicity

- This soil problem caused by high levels of sodium adhering between clay particles is inherent in some Australian cotton soils – the problem can be increased or induced by using irrigation water that is high in sodium levels. Sodicity leads to excessive swelling of the soil and dispersion and breakdown of soil structure. On the surface this can lead to crusting, with associated problems of poor plant establishment and lowered infiltration. At depth it can lead to massive soil structures with reduced pore space that increase problems with infiltration and waterlogging.
- It is possible to address surface sodicity problems with the addition of calcium-based soil amendments such as gypsum and lime. Sodicity at depth can be more of a problem.
- Management should avoid bringing this soil to the surface with tillage operations.
- Use data from a soil test to determine if a problem exists.

Salinity

- In some regions salinity from accumulation of salts within the root zone is a problem. When salt accumulates in the root zone it lowers the amount of water available to plants. Plants become water stressed even if the soil is not dry. Cotton is fairly tolerant of salinity, but rotation crops, especially legumes, can be very susceptible.
- Rising watertables, caused by excessive drainage, can create salinity issues. Conversely, a buildup of salts within the rootzone can also occur from too little drainage, particularly when poor quality water is used for irrigation. This may be a particular issue in dry seasons, especially when using CPLM or drip irrigation (see WATERpak chapter 1.5).
- Management to counteract rising watertables includes lining leaky storages and supply channels. Crop irrigations should be scheduled according to actual crop requirements. If hotspots within the field can be identified, different management on these areas may reduce the salinity problem.
- Management to counteract rootzone salt buildup requires an understanding of the salinity of irrigation water and ensuring the leaching requirement is met. More information on salinity and leaching requirements is included in WATERpak chapter 2.10. A tool for determining the quality of blended water sources is available on the COTTassist website
- Soil test data indicate salinity. Regular soil testing will indicate rising or falling salinity levels (see WATERpak Chappter 2.10).

Low organic matter levels

Low organic matter levels can lead to a lowering of soil stability during rapid wetting, especially in soils that also have a problem with sodicity. Organic matter helps bind the soil in stable aggregates, especially when wetting happens very quickly, as is common with surface irrigation. Organic matter can also partly overcome the effects of sodicity. Soil management practices to enhance organic matter retention include retaining stubble within the field (either standing or incorporated) and the use of minimum tillage principles.

Soil test data can indicate if your organic matter levels are falling or rising over time.

Management issues for soil types common in the Australian cotton industry

Grey and brown cracking clays (vertosols)

In the Australian cotton industry most cotton is grown on this soil type. Features of these soils in terms of irrigation include:

- a high storage capacity for water
- easily damaged if trafficked or worked wet
- self-mulching (repairing)

To manage grey and brown cracking clay soils:

- Be mindful of soil moisture content when working. Use the plastic limit test.
- Controlled traffic limits compaction. Think about traffic wheel patterns in unusual situations.

Controlled traffic has advantages on this soil type - compacted zones in wheel tracks can even be advantageous for support of machinery when the soil is moist.

The key to managing grey and brown cracking clay soils is to be careful of moisture conditions when the soil is worked or driven upon.

A simple test to show if the soil is too wet for working is the **plastic limit test**. Roll some soil from a given depth in your hand. If you can form a ball and then roll a rod shape of 3 mm diameter without the soil crumbling, then the soil is wetter than the plastic limit. Working soil at this moisture content will only remould the soil, destroying pores and creating smeared layers with few pores and high soil strength that makes it difficult for plant roots to penetrate.

To determine if a tillage operation can be completed safely, use the plastic limit test at intervals through the soil profile to the proposed maximum depth of tillage. Don't till into depths that are above the plastic limit.

If there is no option but to traffic the soil when it is wet, for example during a wet harvest operation, think about where wheels will be travelling with respect to existing wheel tracks: that is, try to maximise the number of non-trafficked furrows.

Cracking clay soils are prone to waterlogging because when they are wet, the soil swells and has a tendency to block pores. Soil management to overcome this problem includes:

- ensuring that there is adequate slope on the field to drain excess irrigation or rainwater. Also, ensure the field is level, with no hollows to collect water.
- building hills or beds high. If waterlogging conditions exist lower in the furrow there should still be an area above the water level that is better drained and aerated for at least a proportion of the crop roots.

Addressing compaction

Limited compaction: the current crop may act to remove some of the damage by promoting the shrink swell cycles in the soil. Watch the crop closely for signs of water stress: crops grown on a compacted soil may show signs of stress more quickly than those grown on undamaged soil.

More serious compaction: may be addressed by biological tillage, that is, growing an actively rooted crop such as wheat to dry the soil and promote swell shrink cycles. Note that the more active the root system and the more wet dry cycles the soil is exposed to, the better the result.

Severe compaction: may be addressed by mechanical tillage when the soil is drier than the plastic limit. The tillage can be targeted at specific zones. Use a spade or backhoe pit to determine the existing problem (see SOILpak Part C); for example, a compacted bed shoulder that is causing water infiltration problems could be addressed at nitrogen application time with a curving gas knife.

Sodic soils

Lack of stability of wet aggregates in sodic soil leads to the problems associated with this soil type. In sodic soils, clay dispersion and increased swelling in the subsoil block pores and reduce pore space. This stops or reduces water and oxygen entering the soils, leading to waterlogging problems. Following dispersion of nonstable aggregates (clods) into their individual constituents of sand, silt and clay, surface sealing blocks pores.

Some sodic soils, although initially stable, can become dispersive after being worked at high moisture contents. Soil management for these soils aims at restoring stability to aggregates or clods to prevent their dispersion when wet.

There are simple tests to check if your soil is dispersive. The ASWAT Test (see SOILpak Chapter C4) involves leaving air dry crumbs of soil in distilled water for a period and checking to see if a milky solution of dispersed clay is formed. The stability of the soil following wet working can be deduced by using the same test but using a piece of soil that has been moistened and then reworked before testing.

Sodic soils can also be problematic when building water storages and irrigation systems, as they are prone to tunnelling if compaction of the embankments is inadequate. Tunnelling occurs as water moves through small pathways in the embankment and dispersed particles move with it. If the wetting event is so fast that the clay doesn't have time to swell to fill the resulting pores, tunnelling can occur that can lead to bank failure. If a storage is to be made of this soil type, special attention should be paid to compaction at the correct moisture content and possibly lining the storage with non-dispersive soil (see WATERpak Chapter 1.6).

Management to avoid surface sealing problems

- Some soils have a stable surface layer overlying a sodic dispersive subsoil. Tillage operations can raise the dispersive soil to the surface, creating problems. Be careful when working this soil type.
- Be aware that tillage can create a problem with surface sealing – some marginally stable soils, if tilled at too high a moisture content, that is, above the plastic limit, can become dispersive. Always attempt to till when the conditions are right for your soil.
- Organic matter in the soil acts as glue that holds soil aggregates together. Try methods to maximise organic matter in the soils and to minimise its breakdown. Good organic matter levels can partially overcome the effects of sodicity.

Will gypsum work?

The addition of gypsum can overcome some of the effects of sodicity at the surface. Note however that gypsum will not necessarily work on all soils. If dispersion is identified as a problem, further soil tests should be carried out to see if the soil would respond positively to the addition of gypsum. A soil may be gypsum responsive if it has an exchangeable sodium percentage (ESP) of greater than 5. Calcium to magnesium ration of less than 2 can also aggravate sodicity problems when the soil is near an ESP of 5. In a responsive soil, gypsum will improve surface aggregation (for better seedling emergence), decrease dry soil strength (to give easier tillage), increase water entry (with consequent longer irrigation intervals) and lengthen the time over which soil physical conditions are suitable for unimpeded root growth.

If the soil does not have inherent chemical stability, the presence of organic matter can compensate. Soil management should aim at maximising organic matter in the soil.

Red soils (loam topsoil)

Red soils lack the regenerative capacity of cracking clay soils. Soil structural problems that will self-repair with cracking clays with a wet/dry cycle will not self-repair on a red soil. Damage to red soils should be addressed before sowing.

A soil management bonus of red soils is that they drain quickly and can be trafficked more quickly than clay soils after irrigation or rainfall events.

Soil problems associated with red soils include:

1. Infiltration problems due to hard setting. This hard setting is brought about by a combination of factors that are associated with this soil type including the particle size make-up. The different sized particles found in loam soils can easily pack together, limiting pores for water and oxygen entry.
2. Red soils often do not have enough stable swelling clay (non-sodic) at the surface to encourage self mulching and deep cracking.
3. Low organic matter levels mean that the soil can collapse or slake on wetting (see point 1 above).
4. Rapid surface drying requires irrigation management aimed at watering up rather than planting to moisture.
5. Where red soils are on very permeable subsoils – for example if they are located over recent alluvium – rapid movement through the profile and beyond the root zone results in loss of water from the crop. Aim to manage irrigation to minimise this loss in order to reduce water use and lower the potential for irrigation salinity.
6. Red soils have a very narrow tillage window. The soils can be compacted if too wet and due to low inherent strength they can be reduced to dust if tilled when they are too dry. Avoid the use of disk ploughs and rotary hoes under dry conditions.
7. Where sodicity is also a problem there can be naturally restrictive subsoil layers that prevent irrigation water entry.

Management of red soils

Address problems on red soils before growing a crop as there is limited self-regeneration potential in these soils. Any restrictive layers should be disrupted, keeping in mind that there is a limited moisture window when this can be done without causing damage.

If the soil is in good structural condition, maintain it this way by using minimum tillage, surface mulches, including planting into standing cereal stubble, slow wetting irrigation systems and addition of soil conditioners such as gypsum to maintain the soil structure.

Overcoming red soil problems

Use mulches to minimise the collapse of soil aggregates into micro-aggregates from raindrop impact (this is called **slaking**). Slaking increases as initial water content of the soil decreases and rate of wetting increases, and so slow irrigation delivery methods such as drip and overhead sprinklers (with reduced droplet size and fall distance) can be an advantage.

Slaking under furrow irrigation has been minimised by starting the irrigation with normal discharge siphons, then switching to smaller diameter discharge siphons, although the impact on irrigation performance of this approach should be understood.

Sow into standing cereal stubble to improve infiltration via stable biopores (old root channels). Anchored stubble in the rows also slows down the rate of water movement, increasing the time the water is in the furrow and moving down biopores. When retaining stubble cut it into small lengths to prevent clogging of machinery. Roots should be left anchored.

Trials have been conducted on hard setting soils that showed improved water infiltration over a season. With conventional tillage the soils would not fill the profile following the initial watering. Using a retained stubble system a full profile was achieved with each irrigation. This lowered the irrigations required and increased water use efficiency.

Where fields contain a mixture of soil types including hard setting soils, retained cereal stubble in the systems ensured at least that the hard setting part of the field will receive a full profile.

Further information on the advantages and problems of planting into stubble can be found in the document 'Planting cotton into standing wheat stubble'.

In red soils the short-term benefit of green manure crops can be as much from the production of stable biopores as from the increase in organic matter. Attempt to minimise soil disturbance, especially in the furrow and bed shoulders where biopore retention is important for water infiltration. Try to incorporate stubble with the least disturbance possible, as tillage itself helps speed soil OM breakdown.

Profile inversion using deep mouldboard ploughs can also be used in some cases where a hard setting surface overlies reactive clay. This is in the specific circumstance where the topsoil thickness is not more than 30 cm deep and the subsoil to be brought to the surface is not saline or sodic. The cation exchange capacity of the subsoil should be at least double that of the topsoil. A full soil survey should be done to ensure that this expensive operation would have results.

Deep ripping and chiselling when the soil is just below the plastic limit has been effective in some situations as an alternative to more expensive mouldboard ploughing.

Chisel ploughing furrows in the cotton season when the soil is dry may improve infiltration in the very short term, but there is a big risk of serious damage due to organic matter loss and dust formation from repeated working.

Increasing the time water remains at any given point on a red soil, whilst minimising the amount of tailwater return, is a key to maximising water intake on red soils. As well as the use of standing stubble, 'dammer-dyking' may be of benefit on red soils, especially if planting to fields where no cereal stubble exists. Basically this system involves a machine that places small stops at regular short spacings within the furrow to retain water longer in small puddles. This method is particularly useful under rainfall or overhead irrigation systems. When used in a furrow irrigation system the dams tend to fill quickly with silt unless the depressions are filled with a mulch. The impact of this technique on furrow irrigation performance is unknown, but is most likely negative.

Gypsum application can be of benefit if the clay content of the surface soil is at least 30% with a surface electrochemical stability index (ESI) of less than 0.05. The ESI is equal to electrical conductivity of a 1:5 soil water extract ($EC_{1:5}$) divided by exchangeable sodium percentage (ESP).

Anionic polyacrylamide applied at low rates (7 kg/ha) has been shown to improve seedling emergence and water infiltration in this soil type (see WATERpak Chapter 1.9).

2.6 Soil imaging

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Key points

- Soil electrical conductivity and resistivity can be used to spatially represent soil properties such as moisture, clay content and salinity.
- A number of different instruments are available and are suited to different tasks.
- Some techniques offer detailed information such as multi-depth imaging.
- It is important to ground truth data to known physical properties within the sampling area.
- EM surveys can be used to ensure soil moisture probes are located in representative areas of a field.

This chapter gives a basic introduction into some of the techniques that can be used to provide an understanding of the spatial variability of soil properties. Some of these techniques, such as electromagnetic (EM) devices, are reasonably commonly used across the cotton and grains industries, whilst others such as geolectric (or 'DC resistivity') techniques have had some limited use in specific situations.

For those interested in more detail, the publication [Geophysics for the Irrigation Industry] provides an excellent background to the various techniques and specific pieces of equipment available and covers a range of issues that users of these methods should consider.

Electrical Conductivity

Most of the techniques available for soil imaging measure the electrical properties of the soil which are influenced by the soil texture, moisture and salinity. The most common soil imaging techniques measure either electrical conductivity or resistivity. Electrical conductivity is the ability of the soil to conduct an electric current, whilst resistivity is the inverse of conductivity; in other words, the ability of the soil to impede an electric current.

Electrical conductivity is measured by soil imaging instruments as an average over a bulk sample of the ground. However, the averaging is never uniform within the sampled volume and the values reported by the instrument are termed apparent electrical conductivity (EC_a). It should be noted that that different instruments may report different apparent electrical conductivity depending upon the way they are designed to operate and the heterogeneity of the particular soil.

General Considerations

There are over one hundred different instruments that can be used to measure soil spatial properties, using different techniques and with different characteristics. It is important to understand what information you hope to obtain for your particular circumstance, what technique is best suited and what other issues should be considered.

For example, what specific soil properties are you interested in? Do you want to understand differences in soil type, salinity or soil moisture, and how will you isolate the specific information that you require?

This is usually done by calibrating the measurements against soil samples at a number of locations, but it may also be possible to remove some variables in other ways. For example if a water storage is measured whilst it is full of water, it may be possible to eliminate moisture content as a variable (as all the soil is saturated).

Horizontal resolution is also important, particularly in locations where narrow features such as paleochannels may be likely. In such cases, the footprint of the device and the survey spacing used should have a horizontal resolution small enough to be able to resolve such features in cases where this is important.

Survey depth is a very important consideration. Different devices are designed to measure different soil depths, with some devices also able to measure at multiple depths. The purpose of the measurements will largely determine the depth to be measured and the vertical resolution required, although site conditions may also need to be considered.

One final consideration of particular importance is the impact of metal objects on readings, because instruments measuring electrical conductivity are often strongly influenced by metal objects in their vicinity. However different types of devices may respond to different types of metal objects in different ways, so that an object that creates a significant artefact when using one method may not show up at all when using a different method. It is important to note the location of objects that may cause an issue. Such objects might include fences, pipelines, power lines or machinery.

> *Most EC measuring devices are very strongly affected by metallic objects in their proximity. Shape and grounding of such objects may be very significant. For instance, an ungrounded fence, around a rectangular paddock, with a closed gate may not affect geoelectric devices but may cause problems for electromagnetic devices. Simply by opening the gate, the circuit through the fence may be broken resulting in negligible effect on electromagnetic devices. Similarly, a buried copper pipe may cause problems for a geoelectric device but have less effect on an electromagnetic device.*
>
> *From: Geophysics for the Irrigation Industry*

Some existing surveys have been conducted poorly, although the quality of surveys in general has increased considerably over time as operators have greater experience with the equipment and techniques. It is important for landholders to understand the capabilities of individual contractors and their own requirements for different soil imaging purposes. For example, a contractor who routinely and adequately conducts EM surveys for precision agriculture purposes may or may not have the equipment or experience to conduct detailed investigative imaging to identify preferential seepage paths in a water storage. It may be worthwhile discussing your requirements with a number of providers to find one who best suits your needs for each task.

Imaging techniques

Electromagnetic (EM) surveys are the most commonly utilised technique for imaging in agricultural soils and are most frequently conducted using Geonics EM31 and EM38 equipment, although other devices such as those manufactured by DUALEM are also in use. In typical use, this equipment provides an interpretation of the average bulk soil parameters which provides adequate data for most precision agriculture applications. The commonly used EM equipment provides information to depths of around 1 to 2 metres (EM38) and 6 metres (EM31), although a range of alternative EM meters exist with various characteristics and operating depths.

More sophisticated techniques and equipment are capable of providing additional information such as multi depth imaging. In this case, the nature and thickness of different soil layers can be identified, rather than an average of the characteristics over the total depth of measurement. Such techniques have not been widely used for agricultural purposes but might be particularly relevant for some purposes, for example identifying storage seepage issues. In particular, the presence of seepage pathways (such as sandy paleochannels) which are otherwise surrounded by clay material can sometimes be difficult to identify using EM surveys alone.

Geoelectric devices (often referred to as DC Resistivity techniques) have been used within the cotton industry more recently, although their use is still confined to a small number of cases at this stage. These devices are capable of providing information on soil at specific depths within the soil profile, and operate across a wide range of depths from less than 2 metres to greater than 40 metres. Some devices can also be adjusted so that the total depth of measurement can be varied. These devices require good electrical contact with the ground or water and have been typically employed in research projects with electrodes hammered into the ground to provide a single transect of information. However it is also possible to tow some devices, which is particularly practical on water surfaces and is therefore particularly relevant for identifying soil characteristics in storages.

Other techniques have also been used for specific purposes. For example, Central Downs Irrigators Limited used ground penetrating radar in 2005/06 to investigate possible wall weaknesses on 50 water storages in the Darling Downs region. Around the same time, researchers at the National Centre for Engineering in Agriculture used standard capacitance soil moisture probes to produce two dimensional images of soil moisture under centre pivot and lateral move (CPLM) irrigation (see WATERpak Chapter 5.5). More recently, Anna Greve at the University of NSW has developed a system to investigate three dimensional soil moisture movement using electrical resistivity techniques. Further information on this technique is available on the Connected Waters website and in the Australian Cotton Water Story (p. 53).

Examples of EM and geoelectric surveys for identifying storage seepage are included in WATERpak Chapter 1.6 whilst Chapter 1.5 also contains an example of a geoelectric survey being used to investigate soil moisture changes under cropping and native vegetation as part of a deep drainage study. Further examples are included below. Many additional examples and further information on the various techniques are contained in Geophysics for the Irrigation Industry.

Practical applications of EM surveys

The two case studies of EM application described below are from the irrigated cotton-growing areas of northern New South Wales.

The first is a field in the Namoi Valley experiencing minor cyclical salinity.

The second field, which is located in the Gwydir Valley, has perennial problems with a shallow watertable.

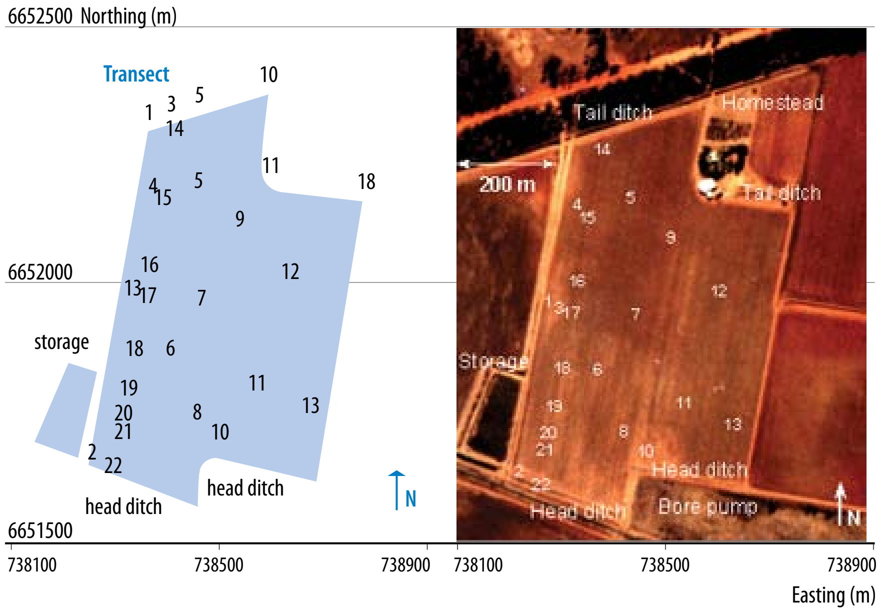
The EM survey helps identify likely causes of soil salinity and clay content in each cotton field studied, and adds value to limited soil information, helping identify where soil samples could be taken to enhance interpretation.

Case study 1, EM application

The first case study is located in the lower Namoi valley near Wee Waa. Figure 5.6.1 shows an aerial photo of a field that is experiencing problems with a shallow watertable and minor soil salinity. The head ditch is located at the southern end of the field next to the water storage.

An EM survey was undertaken to ascertain the extent of waterlogging and soil salinity and the likely causes. Eighteen transects were traversed in a north-south direction in this 29 ha field, recording 20,000 EC_a measurements with the EM38 and EM31 instruments. Twenty-two soil profiles were sampled to a depth of 2.0 m for calibration. Samples were obtained at 0.3 m increments.

Figure 2.6.1. Aerial photograph, location of transects and sampling sites, Case study 1

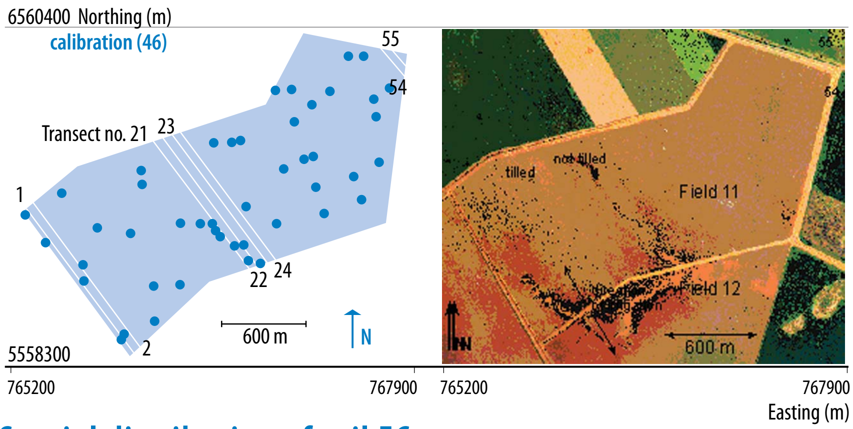


Case study 2, EM application

The second case study is located in the lower Gwydir Valley north-west of Moree. The problem experienced in this field is the presence of a shallow watertable which is causing waterlogged conditions in the middle sections and near the head ditch. Figure 2.6.2 shows the irrigation layout. Again, the head ditch is located at the southern end of the field. A large supply channel and the head ditch of the southern field run parallel to the head ditch of the field.

Fifty-five transects were travelled at a spacing of 48 m. In this field of 240 ha, 27,000 EC_a measurements were made with the EM instruments. The EM survey took two days to complete. A total of 46 soil profile sites were chosen at low, intermediate and high values of soil EC_a for calibration. These were sampled to a depth of 1.5 m.

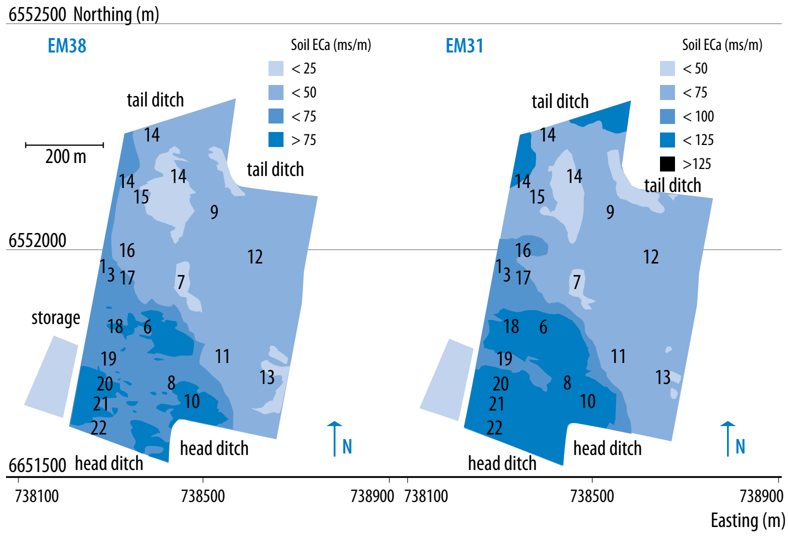
Figure 2.6.2. Aerial photograph, location of transects and sampling sites, Case study 2.



Spatial distribution of soil EC_a

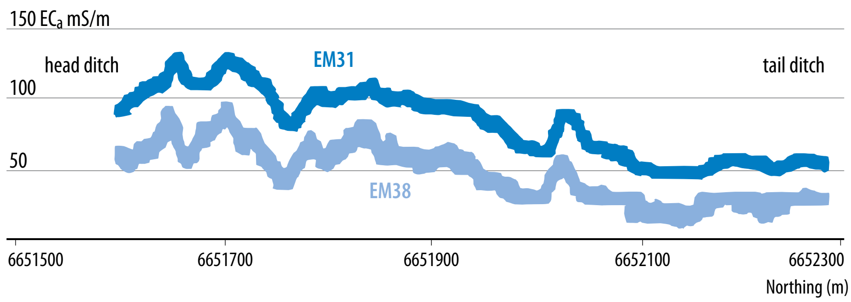
Figure 2.6.3 shows the spatial distribution of EC_a as generated by EM38 and EM31 in Case Study 1. Both instruments show that in the south-west corner, near the head ditch and eastern storage wall, EC_a is higher (for example, EM31 > 125 mS/m) than at the northern or tail ditch end (EM31 < 75 mS/m). This is consistent with where waterlogging is apparent.

Figure 2.6.3. Spatial distribution of EC_a, Case study 1: a) EM38; and, b) EM31



It is also evident that a sharp drop in EC_a occurs approximately halfway between the head and tail ditch. This drop in soil EC_a is shown more clearly in Figure 2.6.4, along transect 3.

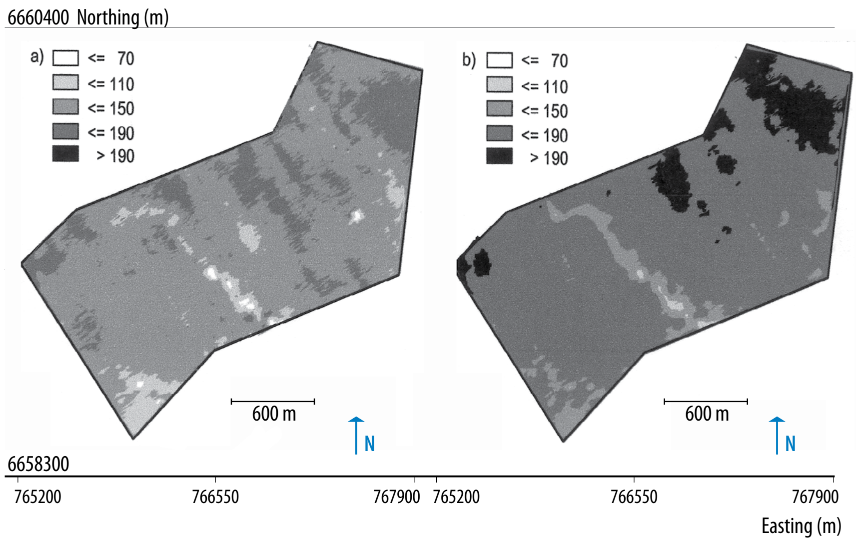
Figure2.6.4. Spatial distributions of soil EC_a along transect 3, Case Study 1.



What is also apparent in Figure 2.6.3b is a small band of low EC_a (that is, <100 mS/m) which lies perpendicular to the eastern storage wall at an approximate Northing of 6651750 (sample site 19). This lower band of soil EC_a is more evident in Figure 2.6.4 for both EM instruments (that is, Northing 6651750).

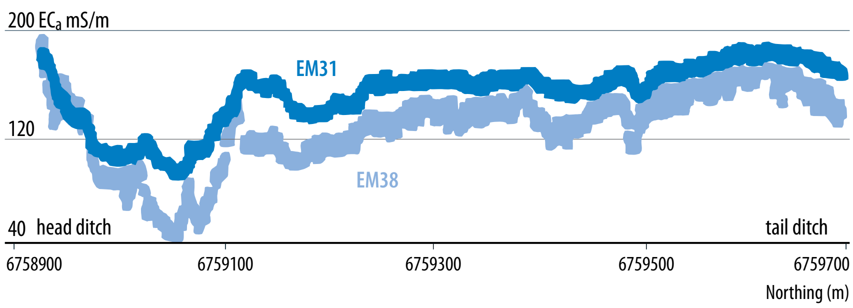
The spatial distribution of soil EC_a generated at Case study 2 is shown in Figure 2.6.5 for the EM38 and EM31. In the north-eastern part of the field, larger values of EC_a (>185 mS/m) were generally obtained with the EM38 and reflect areas where heavy clay profiles exist. Similar, EC_a patterns were obtained with the EM31.

Figure 2.6.5. Spatial distribution of ECa across Case Study 2 for: a) EM38; and, b) EM31 in vertical mode of operation



The lighter shaded areas in Figure 2.6.5 (EC_a < 110 mS/m) indicate parts of the field where a prior stream travelled and where sandier soil types are apparent. This suggests both instruments are primarily responding to clay content and soil mineralogy and hence strongly reflect geology and geomorphology. This is more clearly illustrated in Figure 2.6.6, which shows the spatial distribution of soil EC_a recorded along transect 22 at Case Study 2. The location of the sandier prior stream material is evident between the Northings of 6758900 and 6759100. Further away soil EC_a generally increases and reflects the more clayey soil of the alluvial plain.

Figure 2.6.6. Spatial distributions of soil ECa along transect 22, Case Study 2.



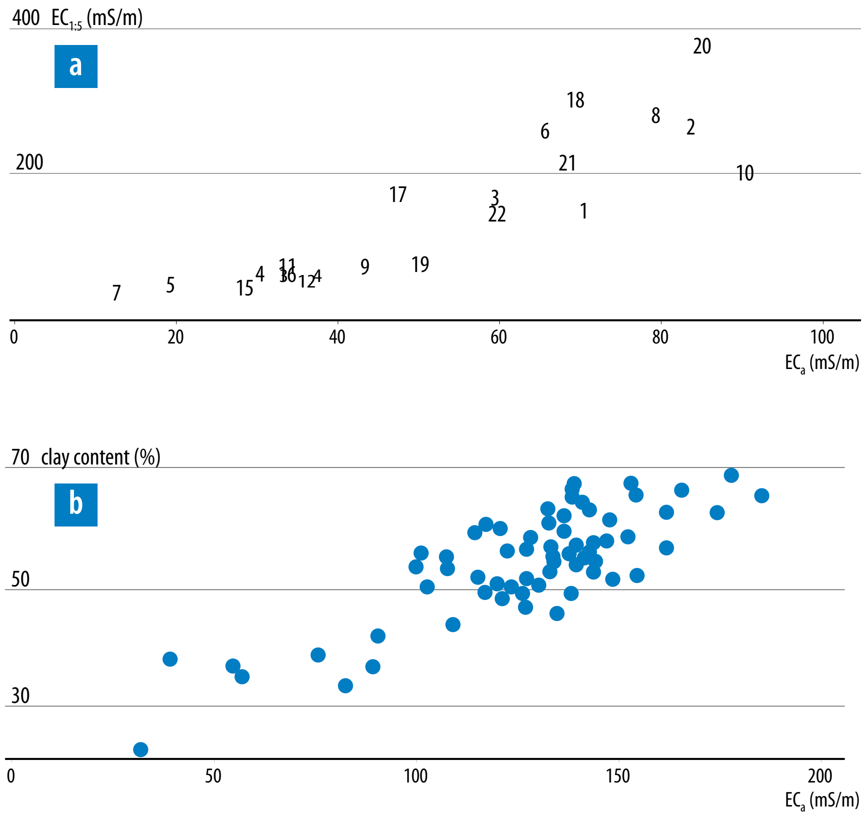
Interpreting soil EC_a

In order to confirm these field observations and determine which soil attributes influence EC_a, average profile values for clay content (%), soil moisture (field moisture %), effective cation exchange capacity (cmol(+)/kg) and soil salinity ($EC_{1:5}$ – dS/m) were determined from the samples collected in each case study. These average profile values were compared with soil EC_a using simple linear regressions.

At Case Study 1, soil EC_a was generally not correlated with average field moisture or clay content. Figure 2.6.7 (a) shows that a reasonable relationship exists between EC_a and $EC_{1:5}$. The low salinity profiles are generally located in the northern half of the field, near the tail ditch. The more saline profiles characterise the southern half near the water storage and where soil EC_a was also much larger. Significantly site 19, which is located in the southern half of the field and lies adjacent to the northeast corner of the storage, does not belong to this group of more saline/high soil EC_a profiles. It is apparent from Figure 2.6.3 that this site does lie within the lower band of soil EC_a as measured by the EM31 and EM38, however.

By comparison, soil EC_a at Case Study 2 was most strongly correlated with average soil clay content and to a lesser extent cation exchange capacity (cmol(+)/kg) and field moisture content (%) to a depth of 1.5 m. The relationship between EC_a and clay content is shown in Figure 2.6.7.

Figure 2.6.7. Relationship between soil EC_a as measured by the EM38 and average a) soil $EC_{1:5}$ at Case Study 1, and b) clay content at Case Study 2.



In summary, the EM system that was developed and deployed provided preliminary soil EC_a information which could be used to determine suitable soil sampling sites. Once analysed for the various soil properties that affect EM instrument response, interpretations could be made as to the likely cause of soil salinity and irrigation inefficiencies in these two irrigated cotton-growing field in northern New South Wales.

At the first case study site, the field is experiencing perched watertables and modest saline soil conditions. This is affecting irrigated cotton production. The probable cause of the problem originates from the storage dam, which has either been constructed poorly or includes soil types which are unsuitable. Further investigation is required and should be targeted at the north-west corner of the storage dam. This coincides with the lower band of soil EC_a apparent in Figures 2.6.3 (b) and 2.6.4. The reason for this is that lower soil EC_a coincides with lower soil salinity ($EC_{1:5}$) as evidenced at site 19. This suggests that the salts have been leached. It is most likely that the movement is lateral through this band of lower soil EC_a because in the adjoining areas soil salinity is quite high at some depths ($EC_{1:5}$ of 6 dS/m). Once the area of leakage has been determined, the dam wall can be reconstructed or lined with impermeable clay membranes.

At the second case study site, the field is similarly experiencing a perched watertable. The problem appears to be due to the location of the supply channel and head-ditch of this field on top of a prior stream channel. Because of the sandy nature of the soil, the supply channel and head ditch are extremely permeable. At the time the EM survey was undertaken, the field was in fallow. However, a shallow watertable was evident when soil samples were taken near the head ditch. The likely management required in this area includes lining the channel with impermeable membranes or re-routing the location of the supply channel to a more suitable area on the farm.

Case Study 3 - Using EM surveys to locate soil moisture probes

Soil moisture monitoring tools are commonly used in the irrigation industry to assist growers like Andrew Parkes of Keytah, Moree and Von Warner, the manager of Bullamon Plains, Thallon with their scheduling decisions. They provide soil moisture information at a specific location within a field. To have confidence in any soil moisture monitoring tool you need to ensure it is located in the most representative part of the field in which it is used to schedule irrigations.

A moisture probe placed in the wrong spot can result in over or under irrigation of the majority soil type in that field. For example, a probe sited in a section of field where the soil is lighter (hence lower water holding capacity) may result in more frequent irrigations than is required for the majority of the field, costing you valuable resources.

EM surveying, used in conjunction with soil sampling, can be used to map soil variations across fields and farms. After ground truthing the instrument by comparing soil samples and EM readings at a number of locations, an EM survey can give an indication of texture changes over the field. Further analysis of this data provides maps of similar soil types and consequently can be used to locate the "majority" soil type within a field.

Andrew and Von are convinced about the benefits of EM soil surveys on their farms. Both growers have used calibrated EM maps to examine soil variability across their fields in order to position moisture probes in sites that are representative of the field, ensuring that their probes are located within the majority soil type, year in and year out.

"Using EM surveys to assist siting moisture probes has given me more confidence with my scheduling decisions" Von said. "It gives me the ability to draw down water and stretch irrigations if necessary". Von did point out that moisture probes are just one tool he uses to schedule irrigations. "Keeping a close eye on weather forecasts and visual inspection of the crop is still vital"

For Andrew, the change in practice for siting moisture probes occurred when capacitance probes first came to the fore. The use of telemetry meant these probes could be placed anywhere in the field. Previously he would position the probe tubes in a section of paddock that looked representative, but was also easily accessed. Back in 2001-02 he was sitting down with Andrew Smart from Precision Cropping Technologies, Narrabri, looking at yield maps.

"I asked him how he knew the probe was placed in the right area in terms of soil water holding capacity." Andrew (Smart) said. "An initial EM survey using an EM38 showed that the EM data on Keytah was heavily influenced by clay content and therefore data from the EM survey could be used to provide a detailed map of potential water holding capacity to around 1.2 to 1.5 metres."

As luck should have it, the probe had been placed in a site that was close to the fields "majority" soil type (and hence "majority" water holding capacity), but the EM survey pointed out the variability of soil in this field. In fact, close to the probe site was a section of field that was much lighter in texture, and the probe could just as easily have been placed in this area.

Because yield maps were also being produced, it was possible to determine that scheduling based on the majority soil type had a positive impact in terms of production. "Yield maps were compared with the data collected from the EM survey and a close correlation between yield and EM readings was found." Andrew (Smart) said.

Figure 2.6.8 shows the relationship between EM and yield, which shows that the majority soil type (with an EM reading of between 120 and 140), matched the areas of the field with the highest yield. This illustrates that they are managing the field and its water based on the majority soil type, as the highest yields are occurring in the majority soil area.

Figure 2.6.8: Relationship between EM reading and Yield (Bales/ha)

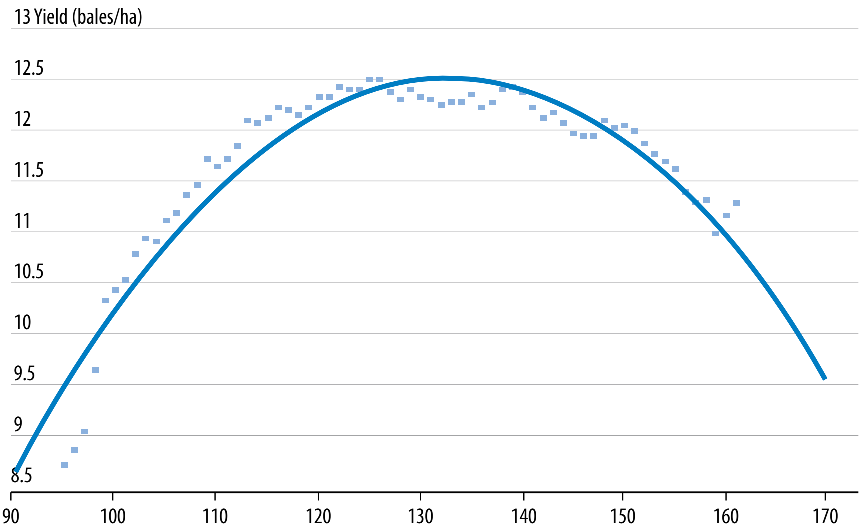


Figure 2.6.9. EM soil variability map

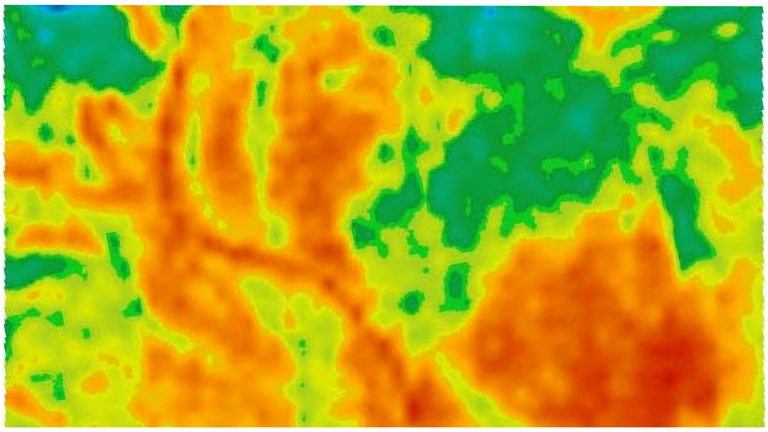


Figure 2.6.10. Slope map to identify possible hollows or ridges

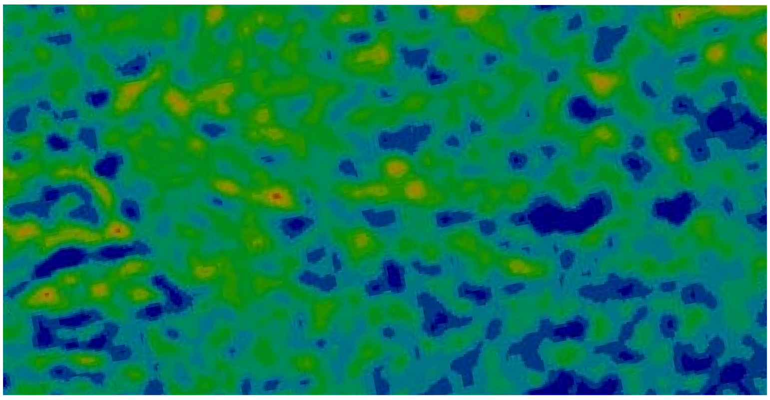


Figure 2.6.11. Combined map showing majority soil type and majority slope

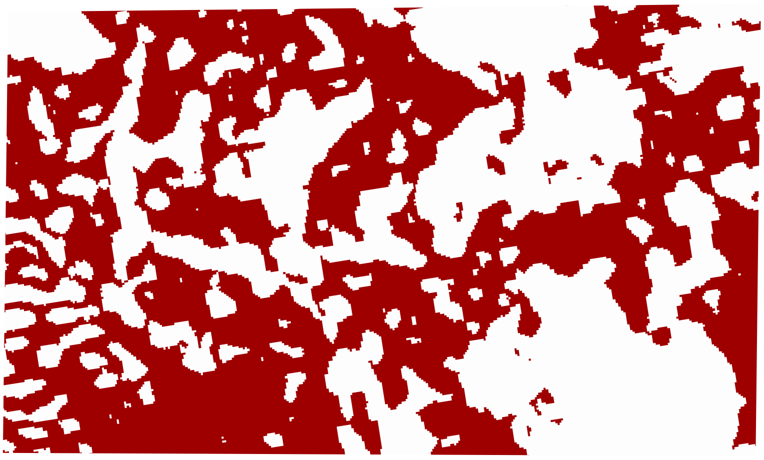


Figure 2.6.8 also shows the lighter soils yielding less because they would have been more stressed from lack of timely water. The higher clay areas or higher EM readings (EC_a>140) were more than likely water logged, but both these soil types only make up a small area of the field.

To refine probe placement, an EM soil variability map (Figure 2.6.9) was overlayed with a slope map (Figure 2.6.10) to analyse variations from perfect plane (to make sure the probe is not placed in a hollow or a ridge) and also a cut and fill map if the field was laser levelled in the last 2-3 years.

These layers of data can then be combined to produce a map (Figure 2.6.11) which best represents majority soil type, closest to majority slope and in some cases removal of areas of high previous cuts and is then used to site the location of the probe in the field. In conjunction with this type of map, Andrew (Parkes) reminds us that ground truthing is still critical, "You need to check your probe is placed in an average plant stand which is also representative to the rest of the field

2.7 Calibrating soil water monitoring devices

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Key points

- Calibration of soil water monitoring equipment is not required to undertake basic irrigation scheduling of crops but is required for advanced tasks such as determining a soil water balance.
- Uncalibrated and calibrated probes will give similar trends, but the real values provided may differ by 40% or more
- The setup, calibration and operation of neutron and capacitance soil water probes is discussed.

Soil moisture sensors, particularly capacitance probes and neutron moisture meters (NMM) have been used for some time in the cotton industry, mostly for irrigation scheduling. These probes are usually used without site specific calibration, and it is important to understand the limitations of probe use under these conditions.

Is Calibration Necessary?

Soil moisture information from capacitance probes and NMMs is usually presented in terms of per cent volumetric water content or 'millimetres' of soil moisture. However, these tools do not directly measure how many 'millimetres' of water is contained within the soil. They instead measure another indicator (electrical conductivity or neutron scattering) and employ a default calibration equation to convert the raw readings into a form that is more recognisable by irrigation managers. The characteristics of the soil in which the readings are taken will determine how accurately the default calibration reflects the actual soil moisture.

For general irrigation management, the accuracy of these readings is less important. What is usually most important is how the current soil moisture compares to the acceptable soil moisture range for optimum crop growth. However, accuracy does become important when soil moisture data is used for some other purposes. Listed below are some common uses for soil moisture tools and some general comments about the need for probe calibration for each of these uses.

Determine when to irrigate (General Irrigation Scheduling)

- Does not require a calibrated probe. Trends of soil moisture extraction can indicate when a plant is beginning to stress. Analysis of soil moisture trends for irrigation scheduling is discussed in WATERpak Chapter 2.1.

Regulated deficit irrigation scheduling (precise scheduling where the soil profile may not be filled)

- Does not require a calibrated probe, although a calibrated probe may provide some additional value. Under deficit conditions, soil moisture can vary spatially, even over short distances (less than 1 metre), so even a calibrated probe may not give a good indication of average soil moisture. A Neutron probe may provide an improved average value under these conditions as it samples a larger soil volume.

Determine volume of water applied/Calculate a soil water balance

- Does require a calibrated probe, although even a calibrated probe may still be inaccurate, particularly under deficit conditions (as mentioned above) or saturated conditions (when probe readings will not increase even though water may still be applied).

Determine actual deficit (e.g. to calculate application efficiency)

- Does require a calibrated probe. Spatial variability may still be problematic under deficit irrigation conditions. Determining accurate crop coefficients and using evapotranspiration data to determine a soil water balance is probably a less labour intensive solution. See WATERpak chapter 2.8 for more information.

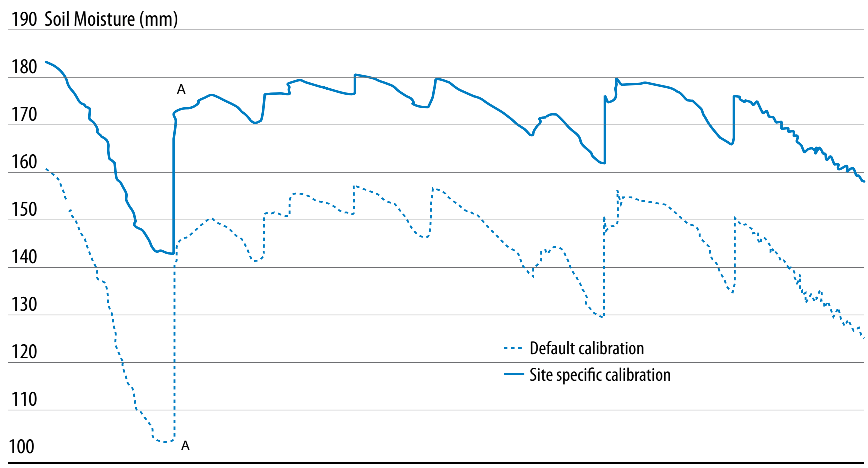
Determine effective rainfall.

- Does require a calibrated probe. Don't forget about the spatial variability of rainfall.

Determine deep drainage

- Even calibrated probes are unlikely to be able to measure deep drainage as this often occurs under saturated conditions. Probe readings will not change under saturated conditions even though drainage may be occurring.

Whilst soil moisture values will differ between a calibrated and uncalibrated probe, the pattern of the soil water trends will be similar. However the magnitude of difference can be significant, which is why calibration is important for some of the uses in the list above. Figure 2.7.1 shows capacitance probe soil moisture data collected from a calibrated site which is then compared to the same data using the default calibration equation.



In this figure, it is clear that the data represents the same trends, regardless of the default or site specific calibration. However if we look at the first irrigation event at point A:

- The calibrated soil moisture (solid line) goes from 144 mm to 173 mm – a change of 29 mm
- The default calibration soil moisture (dashed line) goes from 105 mm to 146 mm – a change of 41 mm

If the default calibration were to be used and assumed to be correct, the change in soil moisture would be overestimated by 40%.

Should calibration be required, it should be understood that the calibration process does require considerable effort. Furthermore, the potential for calibration to change over time in the shrink-swell soils which comprise much of the northern cotton and grain regions should be recognised. This is because probe calibration may vary according to changes in soil bulk density, which might be caused by deep ripping, deep drying or changes to stubble retention practices.

It should be remembered that without calibration these tools have a demonstrated ability to support and improve the process of day-to-day irrigation management, but for other uses the value of uncalibrated data must be considered

Figure 2.7.1 - A single data set using a default and site specific calibration (Sentek, 2001)

Normalisation

It is important at this point to understand the difference between normalisation and calibration. Normalisation (also called the standard count for NMMs) is a process that sets the maximum and minimum readings that a soil probe will encounter. This is done by taking readings in air (i.e. 0% water content) and in water (i.e. 100% water content). The probe can then interpolate readings between these extremes to determine the proportion of water in the medium it is measuring. Normalisation is a standard operating procedure for these tools and should be performed regularly.

The neutron moisture meter

How does a neutron moisture meter work?

The neutron moisture meter (NMM) uses the 'neutron moderation method'. Neutrons are emitted from the probe's radioactive source and are slowed down by collision with hydrogen in the soil water molecules. The meter counts the slow returning neutrons which are related to the amount of water in the soil. The measurement sphere is about a 15 cm radius around the neutron source.

Setting up the NMM

Cable and stops

When cable stops are spaced 10 cm apart, starting 40 cm from the source end of the cable, soil moisture measurements will be taken at 20, 30, 40, 50, 60 cm intervals, and so on, down the soil profile. (These measurements refer to the NMM Hydroprobe® 503DR.) Often from 60 cm depth the cable stops are set every 20 cm apart, giving readings at 60, 80, 100 and 120 cm depths as required.

Standard count

The counts read by the meter are usually divided by a standard count to give a count ratio. A standard count is determined by installing an access tube (sealed at the bottom) into a 44-gallon drum of water and inserting the NMM source probe into the access tube so it is suspended in the middle of the drum. The use of the standard count guards against changes in the count rate brought about by the ageing of the meter's components. The NMM owner's manual explains the procedure for determining the standard count.

Access tubes and installation

Aluminium access tubes sealed at the lower end of the desired length can be installed in the soil by hand or powered augers. Ensure that there is minimal space between the tube and soil. Tubes are installed wherever desired. This could be between rows or on the plant line. Where the irrigation method is drip irrigation, ensure that the location of tube is near a drip emitter so that the site will be watered by the system.

Reading and processing data

Calculating count ratio

The counts read by the meter are divided by the standard count to give a count ratio. The meter counts are usually determined over a 16 second period (if three tubes at one site are averaged) at each position down the profile (see NMM manual to set the count time). It is recommended (but not always undertaken) to determine a new standard count prior to each field NMM soil moisture reading session.

Using calibration curves to calculate 'probe' mm water

When a formal calibration is determined for a neutron probe, a relationship between the count ratio (NMM reading/ standard count) and volumetric water content (**volumetric soil water = % water in the soil × bulk density**) is established for each layer of the soil type in question. This calibration is then site-specific and cannot be used at other sites without errors.

In most on-farm situations the relationship between soil type and count ratio is not assessed, and a default calibration data set is used by most unsuspecting operators.

This relationship might be a straight line of the form:

(a) y=a+bx

where

y is the volumetric soil water content

x is the count ratio

a and b are the regression parameters.

By simply substituting the count ratio for x, volumetric soil moisture content can be calculated.

However for some soil types the relationship might not be linear and could be represented by a more complex equation which introduces a third parameter 'c', for example:

(b) y=a+bxc

To convert this to mm water, simply multiply volumetric water content (y) by the depth interval, which will be 100 mm (10 cm) if readings are taken at 10 cm intervals down the profile:

mm water = volumetric water × depth interval

By adding the mm of water in each depth interval, the total mm of water in the profile is calculated.

Further explanation of these points and of determination of soil bulk density can be found in Dalgliesh, N and Foale, M 1998, *Soil Matters*.

How to get a NMM calibration

Insert NMM access probe tubes into the soil, take NMM readings at intervals (usually 10 cm) down the profile and calculate the count ratio.

Extract soil cores close to the access tube and calculate the gravimetric soil moisture content (see details in *Soil matters*) for each interval corresponding to the NMM interval readings. These readings and cores need to be taken at the soil's upper limit, lower limit and at various moisture contents (intermediate moisture contents) between these limits so that you get a good curve.

Upper limit is the amount of water that a soil holds following drainage for about 48 hours. It can be determined following rainfall or irrigation.

Lower limit is the amount of water left in the soil after a particular crop has extracted as much as it can. This is determined following harvest.

Soil bulk density is required to convert gravimetric soil moisture to volumetric soil moisture. Be aware that although this process seems straightforward, soil samples are required for each depth interval, for multiple soil moisture contents and that bulk density must also be measured.

Calibration for irrigation use

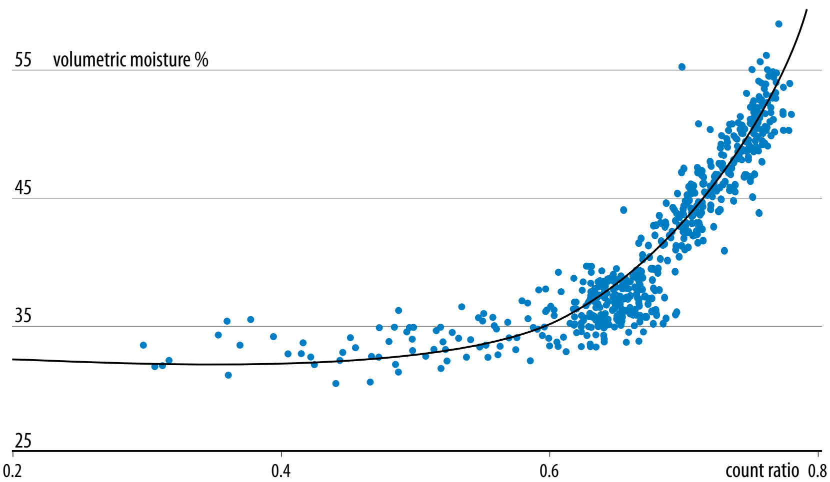
The relationship between the NMM ratio and soil moisture content need only be determined from the upper limit to a moisture content just below the predetermined refill point. Following conversion to volumetric moisture content, the relationship will most likely conform to equation (a) above.

Calibration for rain grown cropping

The relationship between the NMM ratio and soil moisture content will need to be determined from the upper limit to the lower limit and as many points as possible between these. The volumetric moisture content/NMM ratio relationship will most likely conform to equation (b) above, because the relationship between the count ratio and soil moisture content might not be linear as the soil dries to low values.

The volumetric water data are plotted against the NMM count ratio and the relationship calculated for either equations (a) or (b). An example of the relationship for equation (b) is shown in Figure 2.7.2.

Figure 2.7.2. Non-linear relationship of volumetric moisture and count ratio



Capacitance soil water devices

How do capacitance soil water devices work?

Capacitance probes such as the C-probe™ and Enviroscan® systems work by measuring the dielectric constant of soil. Charlesworth (2000) describes the dielectric constant as '*a measure of the capacity of non-conducting material to transmit electromagnetic waves or pulses*'. He adds:

> *The dielectric of dry soil is much lower than that of water, and small changes in the quantity of free water in the soil have a large effect on the electromagnetic properties of the soil water media.*
>
> *Frequency domain reflectometry (FDR) measures the soil dielectric by placing the soil (in effect) between two electrical plates to form a capacitor. Hence 'capacitance' is the term commonly used to describe what the instruments measure. When a voltage is applied to the electric plates, a frequency can be measured. This frequency varies with the soil dielectric.*

(Charlesworth 2000)

Capacitance devices have been shown to deliver repeatability of readings with acute sensitivity to changes in soil water content.

Normalisation is critical for capacitance probes. Without normalising, these devices would only provide a range of irrelevant raw data that varies slightly with each sensor. By matching the raw reading from each sensor to both 0% and 100% water levels, a comparison of readings taken by different sensors can be made on a common scale. This simple action allows raw readings to be seen as either graphics or text permitting irrigators to monitor their soil water levels based on change trends.

Setting up capacitance soil water devices

A number of sensors are allocated to depths within the active root zone of the crop. The number can vary from a couple to eight or more, depending of the level of detail required from the site. Once the location of the sensors has been determined, the sensors are located at their assigned positions on a circuit board that will be installed in an access tube in the field.

Researchers or users seeking absolute values must carry out calibration of the sensors by obtaining a range of values, which are used to produce a calibration curve. A calibration equation can then be determined and described mathematically. This can be done for every sensor and can be done to suit a specific site or soil. This is rarely done for day to day irrigation management, and usually only occurs in the area of research.

The correct siting and installation of access tubes is critical for capacitance devices. As with all devices, capacitance probes need to be installed in a position that is representative of crop type, density and vigour, soil type, irrigation system uniformity and application. Additional care should be taken to locate access tubes where they will not be damaged by machinery. More information on locating probes is included in WATERpak chapter 2.6.

Capacitance probes and cracking soils

Capacitance probes are perceived as being susceptible in clay soils that crack as they dry. This is due to the relatively small soil volume from which capacitance probes source their readings. In practice, this is rarely an issue, and when cracking does occur, the resulting airgaps are easily identified in the software when the soil water content of the airgaps heads towards zero levels. This is well below refill points, and stands out well.

Calibrating capacitance probes

The procedure for calibrating capacitance probes is very similar to that for the NMM:

- As calibration is required across the range of moisture contents from field capacity to crop lower limit (or just below refill point for irrigated crops), a number of sites will be required; one for each moisture content.
- Probe readings should be obtained at each depth for each site.
- Soil cores should be taken close to the access tube and gravimetric moisture content and bulk density determined for each depth at each site.
- Determine volumetric water content as the sum of the gravimetric water content and the bulk density.
- Plot the probe readings against volumetric water content and fit a regression curve. Probe readings should be scaled to take into account the normalisation process. Manufacturers should be able to provide more information on this part of the process.

Sentek provide a very useful calibration guide for their soil moisture probes: check with your manufacturer for further information for your specific device.

Conclusion

Both the neutron and capacitance probes will show changes in soil water content over time and will easily satisfy the requirements of an irrigator seeking to schedule irrigations based on variation in plant water use. Neither probe requires a calibrated unit of measurement in order to achieve this task, as the change in rate of water extraction is used instead. This could in reality be done on raw data alone.

Both types of probes have software that converts raw counts to either a volumetric percentage reading or to a 'millimetre' reading. If this conversion process is not supported with the relevant soil data then the resulting 'millimetre' readings need to be treated with caution.

Where a more accurate unit of measurement is required, there are higher order calibration methods available to correlate the relationship between the raw data counts, actual soil water content levels and the water-holding capacity of the specific soil . This calibration is rarely done in a commercial agricultural situation.

What is the device being used for? Is it being used to schedule irrigation events based on trends in plant water use, or is the device to be used to calculate a full soil water balance?

The calibration of soil water monitoring devices and the comparison of the resulting data are areas where much more work is required. The devices are currently very strong in the scheduling of irrigation events based on changes in soil water levels over time. This is evident in the way most irrigators with scheduling devices determine irrigation events based on graphed data depicting actual plant water use over time.

The debate over calibration should not detract from this ability to support the process of day-to-day irrigation management.

References

Charlesworth P. 2000 'Soil Water Monitoring'. National Program for Irrigation Research and Development Irrigation Insights Number 1

Sentek Pty Ltd. 2001 'Calibration of Sentek Pty Ltd Soil Moisture Sensors' Calibration Manual, 8:27-30.

2.8 Evapotranspiration

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Key points

- Evapotranspiration is the combined loss of water to the atmosphere from evaporation from soil and plant surfaces, and transpiration through plants.
- Many factors affect the rate of water loss by evapotranspiration – the weather, the crop, the environment and management.
- Crop evapotranspiration (ET_c) can be estimated using a crop coefficient (K_c) and a reference crop evapotranspiration (ET_o).
- The Penman-Monteith approach is the preferred method to estimating ET_o.
- Evapotranspiration is difficult to measure directly. It can be estimated using meteorological data or the Class A Pan.
- The Class A Pan must be correctly sited and maintained for meaningful estimates of ET_o to be made. It should only be used for estimates greater than 10 days duration.

Estimates of ET_o can be used to aid irrigation scheduling and calculate evaporative losses from storage and reticulation systems.

A thorough but straightforward introduction to evapotranspiration concepts and scheduling is provided in WATERpak Chapter 2.1 and should be sufficient for most on-farm purposes. The information in this chapter is included for additional background.

What is evapotranspiration?

Evapotranspiration (ET) is the collective term for water lost to the atmosphere by evaporation from a range of surfaces (rivers, dams, channels, soils and wet vegetation) and transpiration through plants. Transpiration results from the vaporisation of water within plant tissues and its subsequent loss through the small openings on the plant leaf called **stomata**.

Evaporation is the conversion of water from liquid to vapour. This process requires energy, energy provided by direct solar radiation and the air temperature. As water is lost to the surrounding air it becomes saturated, and evaporation will slow down if the wet air is not displaced by dry air. The replacement of this saturated air with dry air depends on wind speed. Thus, solar radiation, air temperature, air humidity and wind speed all affect the rate of evaporation. Where soil is the evaporating surface, the degree of shading by the crop and the amount of water available at the soil surface will also affect evaporation. The meteorological factors driving evaporation also influence transpiration.

Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between them. Apart from soil surface wetness, the evaporation from a cropped soil is mainly determined by the fraction of radiation reaching the soil surface. This fraction decreases over the growing period as the crop develops and shades more and more of the soil surface When the crop is small, water is mainly lost by soil evaporation, but, as the crop develops and completely covers the soil surface, transpiration becomes the main process.

The ET rate is normally expressed in millimetres (mm) per unit time – it expresses the amount of water lost from a cropped surface in units of water depth. The loss of 1 mm of water is the loss of 10 m^3 of water per hectare (10,000 litres per hectare).

Factors affecting evapotranspiration

Weather

The weather factors affecting evapotranspiration (ET) are radiation, air temperature, humidity and wind speed. The evaporation power of the atmosphere is expressed by the reference crop evapotranspiration (ET_o): it represents the ET from a standardised vegetated surface.

Crop

Crop type, variety and development stage affect the rate of ET from crops grown in large, well-managed paddocks. Differences in resistance to transpiration, crop height, crop roughness, reflection, ground cover and crop root characteristics result in different ET levels in different crop types under identical environmental conditions.

Environmental conditions

Factors that limit crop development reduce ET – for example, soil salinity, inadequate nutrition, soil compaction, diseases and pests. ET is also affected by groundcover, plant density and soil water content.

Management

The ET rate is also affected by management practices that affect the climate and crop. Here are some of the ET-related effects of management:

- Cultivation practices and irrigation method can alter the microclimate and affect the crop characteristics or the wetting of the soil and crop surface.
- Windbreaks reduce wind velocities and decrease ET rate of the field directly beyond the barrier.
- Micro-irrigation systems that apply water directly to the root zone of crops leave the major part of the soil surface dry, thereby limiting evaporation losses.
- Surface mulches, when the crop is small, substantially reduce soil evaporation.

Evapotranspiration concepts

Reference crop evapotranspiration (ET_o)

ET_o is the evapotranspiration rate from a grass reference surface with specific characteristics. This reference surface resembles an extensive surface of green, well-watered grass with a uniform height of 12 cm, actively growing and completely shading the ground. The soil surface is moderately dry, resulting from a weekly irrigation frequency.

This concept was introduced to study the evaporative demand of the atmosphere independent of crop type, crop development and management practices.

ET_o is only affected by climatic factors. Consequently, it can be computed from weather data. The Penman-Monteith method is recommended as the sole method for determining ET_o because it closely approximates grass ET_o, is physically based, and incorporates both physiological and aerodynamic parameters. Procedures have also been developed for estimating missing climatic parameters.

Crop evapotranspiration under standard conditions (ET_c)

Crop ET under standard conditions (ET_C) is the ET from disease-free, well-fertilised crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions. A crop coefficient (K_C) is used to estimate ET_C from the Penman-Monteith estimate for ET_O, using the formula below:

$$ET_c = K_c \times ET_o$$

ET_C differs from ET_O under the same climatic conditions due to differences in leaf structure, stomatal characteristics, aerodynamic properties and solar radiation reflectance. The crop coefficient for a given crop changes from sowing until harvest, as explained in WATERpak Chapter 2.1 and the DPI Note *Irrigation: water balance scheduling*. Table 2.8.1 summarises the seasonal crop coefficients for various crops.

Table 2.8.1. Crop Coefficients (K_c) for major irrigated field crops.

Crop	K_c initial	K_c mid-season	K_c end of season
Barley	0.30	1.15	0.25
Chickpea	0.40	1.00	0.35
Cotton	0.35	1.15 – 1.20	0.70 – 0.50
Maize	0.30	1.20	0.35
Navy bean	0.40	1.15	0.35
Peanut	0.40	1.15	0.60
Sorghum	0.30	1.00 – 1.10	0.55
Soybeans	0.40	1.15	0.50
Sunflower	0.35	1.15	0.35
Wheat	0.30	1.15	0.25

Standard crop coefficients relate to crops under disease free, well fertilised, optimum soil moisture and full production conditions. Often crops do not meet these conditions, and the crop coefficient (K_c) can be adjusted under these circumstances to better reflect the actual crop conditions. However this may be difficult to do with accuracy, and usually involves at least some additional measurement, for example of leaf area index (LAI). Newly developed tools such a IrriSat can use regular satellite imagery of the vigour of individual fields to provide an improved measure of K_c and hence ET_c.

Determining evapotranspiration

ET measurement

Evapotranspiration is difficult to measure. Approaches used for ET measurement include:

- measure computed from the vertical gradient of air temperature and water vapour via the Bowen ratio method.
- directly measure the flux of water vapour movements using the eddy covariance method.
- estimation of the various components of the soil water balance. This could include cumulative soil water loss measured using soil moisture monitoring tools. Some components such as subsurface flow, deep percolation and capillary rise are difficult to measure. This approach usually can only give ET estimates over periods longer than a week.
- lysimeter studies using crops grown in isolated tanks filled with disturbed or undisturbed soil. A requirement of lysimeters is that vegetation both inside and immediately outside of the lysimeter be perfectly matched. Historically this requirement has not always been the case and has resulted in incorrect ET_c and K_c data.

ET computed by meteorological data

ET is commonly computed from weather data, as it is difficult or expensive to obtain accurate field measurements using the other techniques mentioned. There are a large number of equations that have been developed to estimate ET_o from meteorological data. Some of these approaches are only valid under specific climatic and agronomic conditions. The Modified Penman method has been found to overestimate ET_o, while the alternative Blaney-Criddle and pan evaporation methods show variable adherence to ET_o.

Since 1990, the Penman-Monteith method has been recommended as the standard method for estimating ET_o. The ET from crop surfaces under standard conditions (ET_c) is found from the formula:

$$ET_c = K_c \times ET_o$$

where K_c = crop coefficient

ET_o = reference crop evapotranspiration

The Bureau of Meteorology has developed maps of ET for Australia. The Point Potential ET is calculated using Frederick Morton's potential ET approach. It is very similar to the Penman-Monteith ET_o. These maps have also been published by the Bureau of Meteorology as Wang et al. (2001) Climatic Atlas of Australia – Evapotranspiration.

Daily estimates of Penman-Monteith ET_o can be obtained from a nearby weather station fitted with the appropriate measurement sensors (solar radiation, maximum and minimum air temperature, relative humidity, and wind speed). These weather stations may be at a Bureau of Meteorology site or a research station, or part of a weather station network such as those operated by Hydrodata Networks. Irrigators can also purchase and install their own automatic weather station (AWS).

ET estimated from pan evaporation

Pan evaporation is an historic method of estimating evapotranspiration which has now been replaced by the Penman-Monteith method discussed previously. As Penman-Monteith data is now widely available, pan evaporation methods are no longer recommended. However a short discussion of pan evaporation is included below as this data may still be used in a limited number of circumstances.

Evaporation from an open water surface provides an index of the integrated effect of radiation, air temperature, air humidity and wind on ET.

The standard open water surface used in Australia to estimate ET_o is the Class A Pan. It is a circular pan, 1.2 m in diameter and 250 mm deep. It is made of galvanised iron and mounted on a wooden open frame platform which is 150 mm above ground level. The pan must be level. A stilling well located on the side of the Class A Pan has a level sensor and is used to record the water depth. The pan should be located in the centre of a grassed area, 20 m by 20 m, open on all sides. It should be located in the centre or leeward side of large cropped fields. A bird cage should be used to prevent animals from drinking from the pan.

It is filled with water to 50 mm below the rim. Water is lost from the pan by evaporation. The amount evaporated is determined daily by measuring the amount of water needed to replace that evaporated.

The Class A Pan has been used for over 40 years in Australia. The relationship between evaporation from a Class A Pan and ET_o is given by the formula:

$$ET_o = K_p \times E_{pan}$$

Where K_p = pan coefficient

E_{pan} = pan evaporation (mm/day)

The K_p values vary with the size and state of the upwind buffer zone, the relative humidity and wind speed. It can also vary with the height of the surrounding crop, painting of the pan, and the level at which water is maintained in the pan. For a pan placed in a short green cropped area and 100 m on the windward side of a dry surface, the K_p ranges from 0.7 (with wind speed below 2 m/s and the average relative humidity below 40%) to 0.85 (with wind speed below 2 m/s and the average relative humidity above 70%). For a pan placed in a dry fallow area, 100 m on the windward side of a green crop and with similar conditions, the K_p ranges from 0.55 to 0.75.

Because of the variability in the siting and maintenance of Class A Pans, evaporation from them is not necessarily comparable between pans. The appropriate K_p should be used to adjust data from Class A Pans so that a meaningful estimate of ET_o can be obtained. Using these values to estimate ET_o for periods less than 10 days is not recommended.

Use of evapotranspiration

Estimates of ET_o can be used in several ways. Firstly, they can be used to assist in the design of irrigation systems in order to meet peak water requirements – an example of this is given in WATERpak Topic 5.5 'Centre pivots and lateral move machines'.

Secondly, they can be used to assist in irrigation scheduling decisions. They are the basis of the water balance scheduling approach outlined in *Irrigation: water balance scheduling*.

Thirdly, they can be used to estimate the losses of water from storage and reticulation systems on farm. ET_o estimates can be combined with dam factors to estimate evaporation losses from these systems. Note that local and seasonal conditions will influence the value of the dam factor. Further information is included in WATERpak Chapter 1.6..

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2.9 Using automatic weather stations

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Key points

- Automatic weather stations (AWS) provide site-specific atmospheric information that irrigators can use to assist irrigation scheduling decisions.
- There are a range of factors to consider when purchasing an AWS: sensor availability, accuracy, robustness, method of calculating ET_o, maintenance issues and availability of technical support.
- The siting of the AWS is critical to the accuracy of climatic data recorded.
- Regular and proper maintenance of the AWS is necessary to obtain accurate data.

Purchasing an automatic weather station

There are a number of weather station suppliers and manufacturers in Australia. A fact sheet version of this WATERpak chapter produced by DAFF Qld contains a short list of suppliers, but this list is not updated frequently. Industry irrigation and plant science researchers and extension professionals regularly purchase and maintain weather stations and would be a good source of up to date information on current suppliers.

There are a range of factors to consider apart from cost when purchasing an AWS: for further details, see the Bureau of Meteorology's *Automatic weather stations for agricultural and other applications* document.

Some key factors are:

- The sensors available, their accuracy, precision, and robustness – for ET_o calculations, sensors for solar radiation, maximum and minimum temperature, relative humidity and wind speed are needed.
- If ET_o is automatically calculated by the AWS, determine what method is used; the Penman-Monteith method is preferred.
- Maintenance should be able to be performed on an AWS without affecting the climate record.
- The format of the data output should be simple, flexible, preferably human-readable without reformatting, and independent of the AWS manufacturer. It should also be possible to remotely download data.
- The availability and quality of technical support if the AWS malfunctions.

Siting an automatic weather station

The quality of the weather data from an AWS is a function of the quality of the sensors used and the appropriateness of its siting. Ideally the AWS should be placed in the centre of an open space of at least 50 m by 50 m, which is covered by a short, green grass and surrounded by crops. The site should be on level ground and not shielded by trees or buildings, which would affect the data recorded. It should not be close to steeply sloping land or in a depression where temperatures are frequently higher during the day and cooler at night. Avoid rock outcrops, stone or gravel surfaces near the AWS.

Table 2.9.1 summarises suggested measurement heights and exposure for different sensors in an AWS relative to an existing (or likely future) obstruction such as a growing tree.

Table 2.9.1. Suggested heights and exposure for AWS sensors

Sensor type	Measurement height above ground level	Exposure considerations
Wind	2 m	No closer than 10 times the obstruction's height
Air temperature & relative humidity	1.25 to 2 m	The sensors must be housed in a ventilated radiation shield to protect the sensor from thermal radiation. No closer than 4 times the obstruction's height and at least 30 m from large paved areas.
Solar radiation	To facilitate levelling/ cleaning install at a height of 3 m or less	The sky should not be blocked by any surrounding object. Objects less than 100 above the horizontal plane of the sensor are allowed.
Rain	300 mm (at greater height wind affects the accuracy of measurement)	The sensor should be no closer than 4 times the obstruction's height. The orifice of the gauge must be in a horizontal plane, open to the sky, above the level of in-splashing (that is, above the level of any structures likely to cause splashing into the gauge).

Source: Campbell Scientific Australia 2001; Doorenbos 1976

Varying environmental conditions such as moisture or a growing crop can affect the measurements taken by an AWS in relation to its siting. Three possible effects are:

- the 'clothesline effect', where air passing from dry unvegetated surfaces to moist vegetated surfaces impacts on vapour pressure gradients and heat transfer.
- the 'leading edge effect', where air moves from one type of surface to another surface that differs in temperature, moisture content or roughness. As air passes over the 'leading edge' of this surface change, it gradually adjusts to the new surface. There is a zone where the air is modified but not adjusted to the new surface – placement of an AWS here can give misleading data.
- The 'oasis effect' where an isolated moisture source (a dam or crop for example) is surrounded by a dry area. If the wind draws moist air from the dam or crop, then the relative humidity measurements near this moisture source do not represent the general condition in the area.

Locating an AWS used to calculate ET_o on the roof of a building to make it easier to access data is not acceptable. High air temperatures result from heat convected or conducted from the building surface. The physical and radiative properties of the building material can be important in determining heat loading. A surface with high reflectivity may cause high irradiance values as incoming solar radiation is reflected onto the sensor from the surrounding walls and roof.

Thoroughly discuss the siting of your weather station with your supplier (and don't forget likely future changes in the exposure of the site, through the construction of new buildings or the growth of trees).

Maintenance

Regular and proper maintenance of the weather station is essential to obtain accurate data. The owner of the AWS can carry out routine and simple maintenance. This should include:

- Regular checking and clearing the rain gauge collector of dust and debris. Bird droppings are a particular problem.
- The wet bulb sensor wick should be changed at least weekly throughout the year and more often during hot, windy weather. The water reservoir should be clean and free of algae. To test if the wick is working, feel for moisture at the top of the wick. Replace it if dry and clean the water reservoir. Algae make the wick hydrophobic, causing it to dry out rapidly in hot weather.
- Weekly maintenance is generally unnecessary on AWS sensors used to directly to measure relative humidity. They are prone to calibration drift and are adversely affected by moist or dusty environments. Therefore metallic screens or cellulose acetate film is often used to protect these sensors. Monthly sensor element replacement is necessary if it becomes contaminated. Monthly calibration is also recommended.
- Check the bearing in the wind-run anemometer by listening for any noises as the cups rotate. The cup rotation can also be halted by hand to check for any friction evident at low wind speed. The only way to check the calibration in the field is with a newly calibrated anemometer.
- Check the solar radiation sensor for dust and debris, and clean as required.

More difficult maintenance such as sensor calibration, sensor performance testing and sensor component replacement generally requires a skilled technician and specialised equipment.

Obtaining weather data

Depending on your needs, it may not be necessary to have an onsite weather station as weather data is available from a number of sources. If you are located close to a Bureau of Meteorology weather station, it is possible to download historical rainfall and temperature data for specific years or a more complete data set for the past year. Historical data is also available from the SILO service on a subscription basis.

In some areas, local weather station networks are in place, for example the Darling Downs and Namoi. CSIRO's IrriGATEWAY also has weather stations in Southern NSW and the Gwydir.

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2.10 Irrigation salinity and water quality

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Key points

- Measure soil and water salinity levels on a regular basis to observe trends and identify problems
- Salinisation causes nutritional and osmotic stress on the crop, whereas sodification causes soil structural destabilisation leading to waterlogging.
- Poor quality water can be used for irrigation if appropriate management practices are put into place. These include:
    - Using a higher leaching fraction, with consequently reduced crop WUE.
    - Improving soil structure and soil organic matter, and by supplying appropriate nutrients
    - Avoiding irrigating with poor quality water during the most sensitive stages of crop growth.
    - Using salt tolerant cotton varieties.
    - Diluting (or "shandying") poor quality water with water of a higher quality .

What is salinisation in agriculture?

Salinisation results from the accumulation of soluble salts in the root zone. These salts may be important dissolved salts including cations, such as sodium (Na), calcium (Ca), magnesium (Mg), and potassium (K), and anions such as carbonate (HCO_3), sulfate (SO_4) and chloride (Cl).

In the Australian environment, large quantities of stored salts have accumulated naturally from several sources, including:

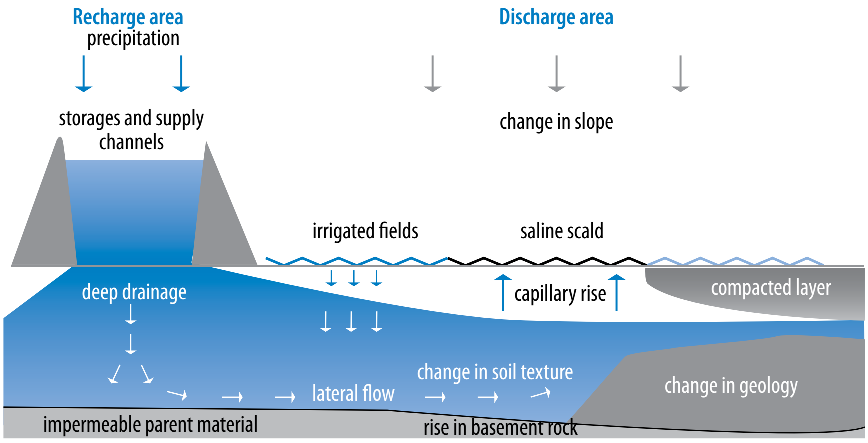
- cyclical deposition through rainfall
- weathering of saline materials, and
- salts stored in the soil or laid down as marine sediments in earlier geological times.

Areas of salinisation are primarily associated with the arid and semi-arid landscapes. These semi-arid and arid areas provide good climatic conditions but, unfortunately, the vagaries of rainfall render them mostly unsuitable for crop production. Irrigation overcomes this, but inefficient irrigation practices usually result in mobilisation of stored salts into the root zone. This is termed **irrigation salinity**.

In terms of agriculture, the other main type of salinisation is **dryland salinity**. Typically it occurs when native vegetation is replaced with pastures or cropping. As a result, less water is used, with the remainder draining beyond the root zone. The excess water (termed **deep drainage**) often recharges groundwater and may cause watertables to rise if the water is unable to flow vertically or laterally because of a change in texture or geology or other obstruction. Any salts stored between the root zone and the groundwater are mobilised in this process and brought to the surface. Through capillary action, salts accumulate and in time will be concentrated enough to cause a reduction in productivity. The capillary rise effect occurs when the dry soil above a watertable draws the groundwater up in much the same way as a sponge sitting on a wet surface soaks up water. The water then evaporates on the surface, leaving the salts behind both in and on the surface soils where they inhibit plant root growth. (See also SOILpak, page D4-5.)

As with dryland salinity, irrigation salinity is the result of significant changes to the hydrological balance in a given area. If irrigation plus rain exceeds evaporation, transpiration and run-off, then recharge of groundwater occurs. The result is excessive deep drainage, which can cause rising or perched saline watertables to appear. Figure 2.10.1 demonstrates how irrigation salinity can occur because of carrying out irrigation or constructing a water storage or supply channel on permeable soil types leading to recharge.

Figure 2.10.1. Schematic representation of irrigation salinity due to permeable soil types



Irrigation salinity occurs in the rice and horticultural areas of the Murrumbidgee and Murray valleys (Australia's oldest irrigation areas) and in cotton areas such as the lower Macquarie, Namoi and Darling river valleys. There is potential for it to become a problem in other cotton-growing areas. In addition, direct application of saline or sodic waters can cause irrigation salinity, since the salts are introduced in the root zone. This is a problem on the Darling Downs and a potential problem in other areas where poor quality groundwater is used.

In order to determine the threat and understand the causes of irrigation salinity, methods and techniques capable of providing this information are required at the field, farm, catchment and regional levels. The identification and measurement of both soil and water salinity are discussed later in this topic.

Cotton and salinity

> *Cotton is more tolerant of salt than most other crops, but salinity problems can easily get to the stage where cotton growth may be retarded. Some of the crops that may have to be grown in rotation with cotton are more sensitive to salt (for example, winter legumes).*

from SOILpak for cotton growers – third edition, C7–1

Cotton is more susceptible to saline scald in early stages of development, a situation compounded by the fact that the highest salt concentrations are found at the top of row crop hills where the crop is planted. Yield decline for adult plants starts at around 7.7 dS/m, with seedlings starting to suffer at around 6.7 dS/m (12% less). A 50 % decline in yield of adult cotton is experienced at levels of 17 dS/m.

Table 2.10.1. Conductivities of saturated extracts and 1:5 soil-water suspensions at which yield decline starts for plants associated with cotton farming systems

Plant salt tolerance	Soil salinity rating	Saturated extract, EC_e (dS/m)	1:5 soil:water suspension, $EC_{1:5}$ (dS/m) Soil texture		
			Silt loam	Medium clay	Heavy clay
Sensitive (e.g. field peas)	Very low	<1.5	<0.16	<0.20	<0.26
Moderately sensitive (e.g. corn, lucerne, broccoli)	Low	1.5–3.0	0.16–0.32	0.20–0.40	0.26–0.52
Moderately tolerant (e.g. cowpea)	Medium	3.0–6.0	0.32–0.64	0.40–0.80	0.52–1.04
Tolerant (e.g. cotton, barley, wheat, sorghum)	High	6.0–10.0	0.64–1.05	0.80–1.33	1.04–1.72
Very tolerant (e.g. saltbush) {halophytes}	Very high	>10.0	>1.05	>1.33	>1.72

Source: modified from *SOILpak for cotton growers*

Field signs of soil salinity are located in SOILpak, section C7-3.

How can we measure salinisation?

On-farm monitoring of salinity levels of both soil and water is easily achieved with commonly available hand-held salinity meters. However, many people have not realised the full potential of these instruments in keeping track of the build-up of salts on the farm and in local waterways.

Salinity meters provide a quick and effective way of monitoring salinity on the farm and in waterways. They are cheap, easy-to-use, and are highly recommended for all irrigators.

The salinity meter is a small and simple battery-powered device that is used to measure the salt content in a solution. This allows a quick and reasonably accurate reading of the amount of salt in water and in soil samples through a simple field test.

By dipping the salinity meter into a solution and measuring the solution's ability to conduct electricity between the electrodes of the meter, you can determine the amount of dissolved salts present. Salts increase the conductivity, so readings increase as salinity levels increase.

The meter then gives a digital readout of the electrical conductivity (EC) of the water, which can be converted to common units of measure for salinity.

Regular testing of water supplies is very important, particularly if bore water is being used for irrigation. Salinity can vary considerably over short periods, and has a profound effect on the growth of plants, especially salt-sensitive varieties.

Table 2.10.2. Common units of measurement for salinity

1 dS/m = 1 mS/cm = 1000 EC (μS/cm) = 640 ppm	So, to convert …		
	From this unit	To this unit	Do this
1 decisiemen per metre (dS/m)	EC (μS/cm)	dS/m	Divide by 1000
= 1 millisiemen per centimetre (mS/cm)	ppm (mg/L)	dS/m	Divide by 640
= 1000 EC (microsiemens per centimetre)	dS/m	EC	Multiply by 1000
= 640 parts per million in water (mg/L)	dS/m	ppm	Multiply by 640

Soil salinisation

In the past, soil salinity assessment involved observing the soil condition (for example, waterlogging, friable soil structure, bare and salt-encrusted surface soil) or plant growth (for example, poor or stunted growth). Whilst this approach provides an approximation, more information is required. This is because soil salinity may reduce crop yields by as much as 25% without any visible symptoms and so salinity might be well advanced by the time the need for control and amelioration is realised.

There are various methods and techniques that can be used to measure or assist in the assessment of soil salinisation, from laboratory measures to field techniques.

In the laboratory, a number of methods have been developed to prepare soil solutions for EC assessment. In Australia, two methods have been used extensively: a saturated soil paste extract (ECe), and a suspended material preparation ($EC_{1:5}$). The prepared extract, suspension, or other preparation is then measured to determine its electrical conductivity (EC). These are always expressed at a standard temperature of 25°C so comparisons can be made under varying climatic conditions.

How to texture soils and test for salinity

Testing a soil sample is a reliable way to assess how salts are affecting plant growth. Even though it is quicker and easier to test water samples, a soil salinity test shows the soil conditions around plant roots, taking into account the influence of soil texture. Identifying current soil salinity conditions and recording salinity trends will help you recognise and predict soil salinity problems.

To perform the test, samples of soil will be required from the crop root zone. If possible, take a sample from below the root zone as well. Aim to take samples from different soil types in an area using electromagnetic (EM) maps with high and low conductivity areas, aerial photos showing waterlogged and saline areas, cut and fill maps showing saline or sodic subsoils and visual signs such as crop variations and remnant vegetation.

Note that soil salinity will be highest before the rain break or before commencing irrigation, so test soils then. Also note that the test result will be artificially high if gypsum (a calcium salt) has been recently added.

The soil salinity field test

Soil salinity can be measured by a simple field test. The test is reasonably accurate in indicating if salts may cause yield losses or soil management problems, but is not as accurate as laboratory analysis.

Commercial soil tests include salinity as one of the properties tested. The field test for salinity is also called an $EC_{1:5}$ ('EC one-to-five') test because a ratio of 1 part soil sample to 5 parts distilled water is used to find the salinity of the sample.

The three steps in a soil salinity test are:

1. Assess the texture of the soil sample.
2. Measure the salinity of a solution made up of distilled water mixed with the collected soil.
3. Multiply the test result by the conversion factor based on soil texture to get soil salinity (EC_e), which shows how soil salinity will affect plant growth.

In simple terms, a given amount of salt in sandy soils will be more concentrated in its effect on plant roots than an equivalent amount in clay soils. This is because sandy soils hold less water to dilute the salts than clay soils (they have a lower available water content). Find the multiplication factor for your textured soil sample on the conversion factor table (Table 5.3.3).

Table 2.10.3. Coefficients for converting $EC_{1:5}$ (S/m) to an approximate value of EC_e (S/m) based on soil textural properties

Texture class	Textures	Clay (%)	Coefficient
Sands	Sand, loamy sand, clayey sand	<10	-
Sandy loams	Sandy loam, fine sandy loam, light sandy clay loam	10-20	11
Loams	Loam, loam fine sandy, silt loam, sandy clay loam	25	10
Clay loams	Clay loam, silty clay loam, fine sandy clay loam, sandy clay, silty clay, light clay	30-40	9
Light clays	Light clay	35-40	9
Light medium clays	Light medium clay	40-45	8
Medium clays	Medium clay	45-55	7
Heavy clays	Heavy clay	>50	6

Source: after Daniells and Larsen 1991

Water salinity

Surface water tests provide a reading that is accurate only at the time of testing. The salinity can change sharply in a short time due to evaporation or rainfall, so water needs to be tested regularly.

- River water supplies can change, with good quality water often being interspersed with slugs of higher salinity water flowing downstream.
- Groundwater tends to be more constant in the short term. Groundwater should be checked on farm for watertable depth and salinity levels, and more importantly for any changes.

Test wells, observation wells and piezometers are an easy way of measuring the level of the local watertable, and can highlight potential salinity hazards on your property before they become a problem. They measure the free water depth to the local watertable, and give an indication of what is happening to the local watertable.

They are best located:

- in problem drainage areas
- on low parts of the farm
- on light permeable soils (especially areas of prior stream or old watercourses)
- in a non-irrigated areas adjacent to irrigation
- next to large storages and supply channels
- where signs of salting are occurring
- in areas you suspect may have high watertables.

Testing water salinity

Some points to consider when testing water for salinity are:

- Make sure that the water sample is mixed thoroughly prior to testing.
- Rinse the sample container with sample water before collection.
- When sampling from a storage, collect a sample from entry points, and several locations around the storage.
- When sampling from a channel or river, collect a sample from near the middle of the flow and near your pump intake.
- When sampling from a bore, collect a sample from a turbulent area near the discharge pipe, after continuous pumping for at least 30 minutes.
- When testing water from a testwell or piezometer, bail out the water in the pipe and allow fresh groundwater to enter prior to testing.
- Salinity meters should read zero in the air and if not they need to be calibrated.

Crop production can decline if the salts in irrigation water exceed certain levels. It may be difficult to recognise salinity problems in the paddock because there can be a significant yield decline before the signs of salinity are obvious. There may be no obvious plant symptoms or signs of salt on the surface. Some early visible signs for most irrigated plants may be:

- slow or patchy germination and establishment
- stunted growth
- burnt leaf tips. The whole plant may start to lose its vigour and healthy green appearance and appear yellow or bronzed (especially if it is also waterlogged).

In cases where salinity is severe, salt-tolerant plants such as sea barley grass or couch may become more evident.

Table 2.10.4. General water quality benchmarks (in dS/m)

Water type	dS/m
Distilled or rain water	0
Desirable limit for people	0.83
Environmental impacts may occur	1.5
Safe limit for people	1.56
Limit for mixing herbicides	4.7
Seawater	55+

The effects of water salinity on plant yield, where the water of a set salinity level is used for the whole irrigation season, are shown in Table 5.3.5.

Table 2.10.5 Tolerance of crops and pastures to water salinity and root zone soil salinity

Soil type	Water salinity limits for surface irrigation (in dS/m)						Root zone soil salinity (in dS/m)	
	Well-drained soils		Moderate to slow draining soils		Very slow draining soils			
Yield reduction	Up to 10%	25%	Up to 10%	25%	Up to 10%	25%	Up to 10%	25%
Pasture legumes								
Strawberry clover	2.1	4.0	1.4	2.6	0.7	1.3	2.1	4.0
Lucerne (most varieties)	2.0	5.4	1.3	3.5	--	--	2.0	5.4
Lucerne (salt tolerant varieties)	3.6	5.9	2.4	3.9	--	--	3.6	5.9
Pasture grasses								
Phalaris	4.2	8.0	2.8	5.3	1.4	2.6	4.2	8.0
Perennial ryegrass	5.6	8.9	3.7	5.8	1.8	2.9	5.6	8.9
Tall wheatgrass	7.5	13.3	5.0	8.8	2.5	4.4	7.5	13.3
Saltbush	12	20	8.0	13	4.0	6.6	12	20
Puccinellia	16	22	10.6	15	5.3	7.3	16	22
Winter crops								
Wheat	6.0	9.5	4.0	6.3	2.0	3.1	6.0	9.5
Canola	6.5	11	4.3	7.3	2.1	3.6	6.5	11
Barley	8.0	13	5.3	8.6	2.6	4.3	8.0	13
Summer crops								
Grain sorghum	1.0	1.5	0.7	1.0	0.3	0.5	1.0	1.5
Maize	1.7	3.8	1.1	2.5	0.6	1.2	1.7	3.8
Soybeans	2.0	2.6	1.3	1.7	0.6	0.8	2.0	2.6
Sunflowers	5.5	6.5	3.6	4.3	--	--	5.5	6.5
Cotton	7.7	12.5	5.1	8.3	2.5	4.2	7.7	12.5

Plants can be watered for short times with saltier water, if fresh irrigation water is available later to flush away the salt and the groundwater is deep enough to allow adequate leaching. Saline water can also be shandied with better quality water to reduce the effects of salts and sodium in irrigation water. However, shandying will diminish the useability of good quality water and should only be used if the quantities of good water far exceed the quantities of poorer quality water. A tool for determining the resultant water quality when mixing different water sources is available on the CottASSIST website.

The values listed in Table 2.10.5 can vary with:

- stage of plant growth: plants are much more susceptible to salinity at germination and seedling stages.
- soil type: influences potential for leaching of salts. If salts cannot leach away from the surface and plant roots it will cause more damage. Water moves through heavier soils (clays) more slowly, so salts in the water are more likely to affect plant growth.

- method of irrigation: spray irrigation concentrates salts and chlorides on leaves and can cause leaf scorching. **Use caution when irrigating with sprays if the water salinity is above low levels.** Leaching of salts is lower under drip irrigation systems but still possible.

Some tips on using saline water

- Use the best quality water when establishing crops, as plants are much more salt sensitive when germinating and when young (especially lucerne and clover).
- The best time to use poorer quality water is in the late summer–autumn period for pre-watering winter crops. Older, well-established plants are more salt tolerant than young plants, winter cereals are more salt tolerant than most other crops and there is less accumulation of salts in the surface soil over the season.
- Avoid filling storages with saline bore water. This water tends to have more salts than channel or freshly recycled water. These salts will build up in time (through evaporation) in the storage, causing the water to become saltier, increasing the leakiness of the storage, and damaging the clay lining. If the bore water is sodic (contains too much sodium), then the clay lining is more likely to slake or disperse: muddying the water in the storage, and possibly breaking down the clay lining and banks.

Management and remediation of irrigation salinity

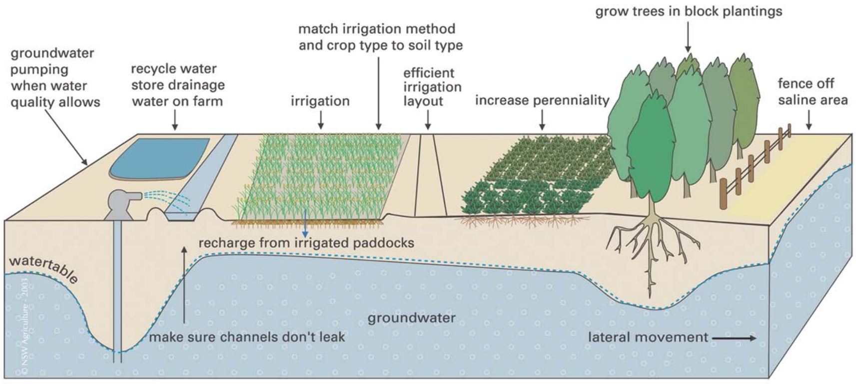
In order to minimise salinity impacts and to improve affected sites, land needs to be managed according to its level of soil salinity. Irrigators need to know their soil types, watertable depths (especially around storages and major supply channels), their current salinity levels for soil and water and the potential risk for further degradation due to salinity.

The land that is most suited to agricultural production has low (0 to 2 dS/m) to moderate (2 to 6 dS/m) levels of root zone salinity. This land has little to no effect on production at the low end and minor yield losses at the high end. This is due to mobilisation of salt into the root zone through capillary rise. There is risk however of further salinisation and visual indications will point to this.

Land that requires protection measures is land with high to extreme levels of root zone salinity, that is, 6 to 15 dS/m and over. Surface salts will affect all plants, and at these levels there is probably a shallow watertable. Change in species composition to highly salt tolerant plants and the appearance of bare patches will be evident. Land at this level of salinisation requires the establishment and maintenance of a perennial groundcover. Irrigated crops can be used to leach away surface salts if there is no shallow groundwater but the land has a high risk of further salinisation. Soils over 15 d/S m are considered extreme, and sites affected have extensive scalding. Most vegetation dies out, leaving only salt-tolerant plants (halophytes). Regeneration of these sites is difficult and requires careful management and protection.

In all cases irrigations need to be scheduled to match plant water requirements at differing stages of the season. The plant requirements continually change due to climatic conditions, rooting depth, stage of growth and are also influenced by soil type. The irrigation water applied should match this crop need in both the amount applied and when it is required. Excess drainage through over-irrigation needs to be prevented if irrigation salinity is to be avoided or reduced in salt prone areas. In areas where it is difficult to manage surface irrigation and its excess drainage, then more precise irrigation methods such as drip and spray could be considered.

Figure 2.10.2. Irrigation salinity management control



Irrigation salinity management control. Source: Southern Salt Action Team 2004.

Irrigation channels and storages should be monitored for leakage. Leaks should be fixed where possible. In worse case scenarios, channels should be re-routed and storages used for short-term storage only, split or even abandoned. Groundwater pumping and subsurface drainage are both methods that are currently used with success to control the impacts of irrigation salinity in some irrigated areas of Australia. At this level of remediation, early prevention is much easier and cheaper.

Early prevention focuses on the correct design of systems, whole farm planning, sound irrigation management, good understanding of the mechanics of salinity and vigilant monitoring for changes in saline conditions.

Irrigators should concentrate their resources such as irrigation water, diesel, seed and fertiliser onto the land suited to agricultural production instead of onto land with higher levels of salinity. Land with low to moderate levels of salinity will give a higher economic return.

On the land best suited to production, ensure that the irrigation-based agricultural systems used maximise the amount of soil water they use, avoid leakage to the watertable beyond the root zone and hence prevent potential salinity problems. Where shallow watertables exist, plant salt-tolerant deep-rooted perennials to draw down the watertable. Also plant trees in targeted areas to intercept lateral groundwater table flows and also draw down shallow watertables.

Land management practices such as effective irrigation management, surface and subsurface drainage, and maintaining groundcover can be used to reduce soil salinity levels. The aim is to maintain soil salinity at a level where agricultural production can occur.

On-farm water quality

Whenever poor quality irrigation water is used, the consequences on cotton crops and soils must be considered. This has become increasingly important in recent years when, for example, drought reduced the availability of good quality irrigation water and many cotton growers reluctantly irrigated with water of poor quality.

Poor quality irrigation water is enriched with salts and nutrients. Consequently its long-term use can cause reductions in cotton growth and soil degradation. These consequences can be minimised or avoided by vigilant crop and soil management, which does, however, involve additional costs. Treated sewage effluent and other industrial waste water which superficially appears to be cheaper than river and bore water has hidden costs in terms of crop and soil management.

Chemically, such water is characterised by high salt (Na and Cl) concentrations and, less commonly, high nitrate and phosphate concentrations, high sodicity, and high alkalinity. Higher concentrations of K are also not unusual. As this water is recirculated, it tends to become turbid faster due to soil dispersion caused by the sodium. The dispersed clay particles in the water also carry adsorbed nutrients and salts. Poor quality irrigation water is commonly bore water, treated sewage effluent or other industrial wastewater, although the quality of recirculated water is also poor as it contains both salts and nitrates picked up as it moves around the farm.

An example of the amounts of salts and nutrients which enter a cotton field in recirculated bore water and treated sewage effluent is given in Table 2.10.6. Assuming uniform concentrations and irrigation efficiencies typical of much of the cotton industry, about 60% to 70% of the salts and nutrients in irrigation water will be retained in the soil.

Table 2.10.6. Quality of treated sewage effluent (Narrabri, NSW) and re-circulated bore water (Merah North, NSW)

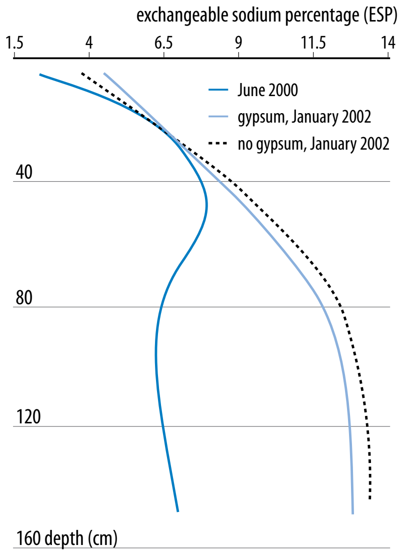
Irrigation date	pH	ECw dS/cm	K kg/ha	Ca kg/ha	Mg kg/ha	Na kg/ha	Cl kg/ha	NO_3-N kg/ha	SAR
Treated sewage effluent									
15-Oct-01	8.8	0.71	3.4	13.6	6.4	91.7	843	26.8	5.1
23-Dec-01	8.7	0.69	9.1	11.9	7.2	151.8	858	50.3	8.5
21-Jan-02	8.9	0.73	4.7	8.0	3.7	78.5	977	29.7	5.7
30-Jan-02	8.7	0.71	15.5	13.0	7.7	172.2	1047	46.2	9.3
18-Feb-02	9.2	1.15	8.9	11.2	6.1	119.3	1182	56.6	7.1
8-Mar-02	9.7	1.38	7.7	6.6	5.8	122.7	932	36.8	8.4
Seasonal total			49.2	64.3	36.9	736.2	5840	246.5	
Recirculated bore water									
19-Sep-00	9.1	0.43	2.1	14.1	13.6	54.4	1786	6.0	2.5
6-Oct-00	8.1	0.35	1.6	14.5	8.8	36.6	1626	43.9	1.9
13-Dec-00	8.2	0.52	2.4	12.6	8.2	86.9	1562	15.5	4.7
28-Dec-00	8.1	0.40	2.3	15.1	11.4	59.5	320	57.2	2.8
9-Jan-01	8.2	0.40	1.9	17.0	11.8	56.3	249	4.5	2.6
18-Jan-01	8.2	0.41	2.0	13.8	12.0	68.5	238	2.6	3.2
29-Jan-01	7.8	0.46	2.0	17.0	11.9	72.2	399	31.1	3.3
16-Feb-01	8.2	0.34	2.4	13.1	9.0	41.2	178	37.6	2.1
21-Feb-01	7.7	0.68	3.3	17.1	16.3	94.7	195	16.0	3.9
Seasonal total			20.0	134.3	103.0	570.3	6552	214.4	
River water (Namoi River)									
12-Oct-00	8.7	0.45	5.3	20.4	22.3	41.9	32	29.2	1.5
5-Jan-01	-	0.58	6.6	37.9	21.6	40.0	749	6.8	1.1
19-Jan-01	7.6	0.41	3.7	21.9	18.6	34.9	309	2.8	1.3
Seasonal total			15.6	80.2	62.5	116.8	1090	38.8	
7-Nov-02	8.5	0.27	2.1	15.6	14.2	20.9	249	2.8	0.9
17-Dec-02	8.3	0.25	2.9	11.4	12.3	20.5	245	1.1	1.0
15-Jan-03	8.2	0.28	3.1	16.9	14.6	21.5	199	15.4	0.9
29-Jan-03	8.2	0.21	2.1	13.6	10.3	12.8	167	3.1	0.6
19-Feb-03	8.2	0.27	3.5	12.5	15.6	21.5	217	9.2	1.0
Seasonal total			13.7	70.0	67.0	97.2	1076	31.6	

Notes: Values are an average of 3 fields sampled from the head ditch. For comparison, qualities of river water used at ACRI during the 2000-01 and 2002-03 seasons are also shown.

Nutrient entry to the field (in kg/ha) has been calculated on the basis of an irrigation rate of 1 ML/ha. (EC_w is the electrolytic conductivity of the water, a measure of its salinity, and SAR is the sodium adsorption ratio, a measure of its sodicity. As a general rule of thumb, irrigation water which has $EC_w \leq 0.4$ and SAR ≤ 4 is considered to be good to excellent).

Irrigating with poor quality water, then, can result in soil salinisation, sodification and nutritional stress. Figure 2.10.3 shows an example where soil profile sodification was caused by irrigation with treated sewage effluent.

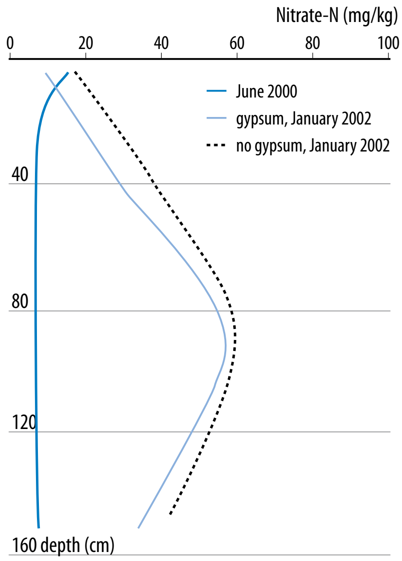
Figure 2.10.3. Effect of gypsum and time on ESP



Note: although gypsum was added, it was not sufficient to prevent sodification.

In addition, excessive amounts of nitrates and phosphates in the irrigation water can move into the watertable and cause pollution of drinking water sources. Figure 2.10.4 shows an example where nitrate in irrigation water (treated sewage effluent) was not used by the cotton crop but has moved deep into the soil profile.

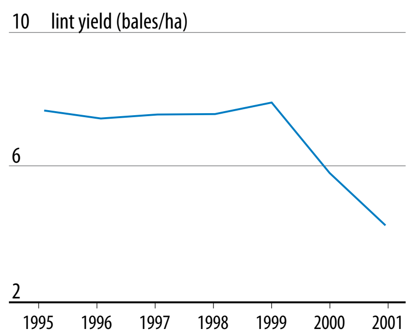
Figure 2.10.4. Effect of gypsum and time on nitrate N concentration



Soil salinisation will result in osmotic (salt-induced water deficiency), nutritional and toxic stresses in crops, whereas sodification causes nutritional stresses, toxicities and soil structural destabilisation. The latter will lead to poor root growth and waterlogging (see SOILPak for more details).

Commonly seen nutritional stresses are K and P deficiencies, and Na and Cl toxicities. Long-term irrigation with poor quality water usually shows up in cotton crops as stunted growth, premature senescence and declining yields (Figure 2.10.5).

Figure 2.10.5. Change in average cotton lint yield at Merah North, 1995-2001. Irrigation water quality deteriorated after 1999



In many fruit crops, Cl toxicity shows up as burns and necrotic lesion on leaves, but in cotton, at the concentrations seen in Australia, Cl toxicity is more likely to be seen as stunted growth due to N deficiency, even though there may be sufficient nitrate-N supplies in the soil. This is because Cl can block uptake of nitrate-N by the cotton crop.

With some sources of poor quality water, such as treated effluent, which has high concentrations of K (for example, about 45 to 60 kg K/ha/season) compared with irrigating with river water (usually less than 10 kg K/ha/season), K deficiency is less likely to occur. P concentration is also high in treated effluent, so P deficiency is also less likely to occur.

Managing poor quality irrigation water

Measure on-farm water quality

Water quality measurements are vital to diagnose issues and determine appropriate management responses. Importantly, regular water quality monitoring may help to proactively identify potential issues before negative consequences occur. As indicated in the case study at the end of this chapter, water quality can vary substantially over time and even between closely located water storages. It is also a Level 2 requirement of myBMP that water quality of all major sources is measured where risks are identified.

Basic water quality testing can be undertaken simply and cost effectively. Salinity meters can be purchased inexpensively and inexpensive test kits for nutrients and pesticides have recently been developed. Further information can be obtained from the Cotton CRC website or the Australian Cotton Water Story (pages 98 and 104).

Avoid irrigating with saline water during periods when cotton is sensitive to salinity

As young cotton between 2 and 10 weeks aft er sowing is very sensitive to salinity and the mature crop is relatively insensitive, either river or bore water of low salinity or stored rainfall should be the preferred source of water for early season irrigation. Alternatively, 'shandying' of poor and good quality water may be attempted.

As the crop matures and becomes more tolerant of salinity, water of higher salinity can be used for irrigation.

Include a leaching fraction when irrigating

If you are using saline water, a leaching fraction of up to 20% is recommended for most clay soils. This means that an additional amount of water of the order of 20% over that required by the crop is needed to allow the salts which come in with irrigation water to be leached out of the crop's root zone. Consequently water use efficiency of saline water-irrigated crops is lower than when good quality water is used. The disadvantage of using a leaching fraction is that nutrients in irrigation water are also leached out of the root zone.

The leaching requirement to maintain the potential yield for cotton (saturation extract EC = 7.7 dS/m) was measured as part of recent deep drainage trials (see WATERpak Chapter 1.5). This work found that for good quality irrigation water, the required leaching fraction was typically less than one to two per cent. However for poorer quality water (EC = 4.15 dS/m), the required leaching fraction was 12.1 per cent.

The same research also found that whilst there may be some seasons where there was no deep drainage under furrow irrigation, in most cases the average deep drainage was sufficient to satisfy the leaching requirement. However, under CPLM irrigation, a number of seasons of zero drainage were noted, with subsequent build up of soil EC. In such conditions, monitoring of soil EC would be beneficial to ensure that soil EC remains within acceptable limits.

The specific leaching requirement for a given set of crop, soil and water parameters can be calculated using the procedure in the ANZECC Guidelines Volume 1 and Volume 3. Calculations can also be undertaken using tools such as SALFPREDICT.

Manage soil to improve and maintain good soil structure

Good profile soil structure will facilitate leaching of salts which come in with poor quality irrigation water. Management practices which improve soil structure are explained in detail in SOILpak. Briefly, these practices are:

- Using soil amendments such as gypsum, lime or lime/gypsum mixtures, synthetic polymers such as polyacrylamide (PAM), or organic amendments such as composts.
- Using suitable rotation crops to improve subsoil structure. In sodic or saline-sodic soils, rotation crops which are tolerant of sodicity and salinity should be used. Cotton and cereal crops such as wheat, sorghum or forage sorghum can tolerate levels of salinity and sodicity which most grain legumes cannot. Leaching of salt is, therefore, less with most grain legumes. Other crops tolerant of salinity and sodicity are tall wheat and couch grass, barley and Egyptian and Persian clovers. In extreme situations, saltbush and bluebush can be used.
- Minimum ('permanent beds') or zero tillage, particularly when combined with controlled traffic systems, improves soil structure more than conventional tillage systems.

As with using a leaching fraction, the disadvantage of improving soil structure is that nutrients can be potentially leached out of the crop root zone.

Retain salts and nutrients in a 'filtration' field

Saline irrigation water may be passed through a cotton field sown into standing wheat stubble (Figure 2.10.6). As infiltration is higher with standing stubble, salts and nutrients are retained in the field by being moved into the soil profile, and not circulated with recycled irrigation water throughout the entire farm. That is to say, the water which leaves this field is hopefully cleaner than that which entered it (Figure 2.10.7). The salts which were retained in field (Figure 2.10.8) are then leached out of the cotton root zone over time.

Figure 2.10.6. Cotton sown into standing wheat stubble near Narrabri, NSW

Figure 2.10.7. Run-off water from adjacent plots of cotton sown into standing or incorporated wheat stubble (left) standing stubble (right) stubble incorporated

Figure 2.10.8. Exchangeable sodium percentage in adjacent plots of cotton sown into standing or incorporated wheat stubble, November 2001, near Boggabri, NSW

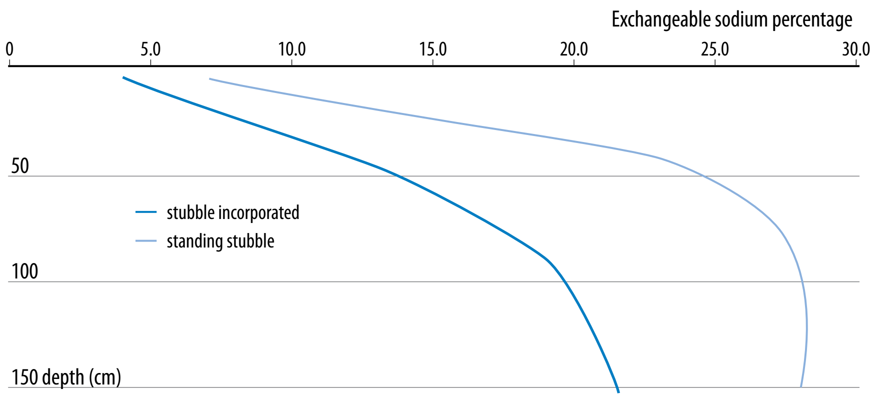


Figure 2.10.9. Clearing standing wheat stubble from furrows with sweeps.

(A) Uncleared furrow with standing stubble , (B) Side view of sweep used in operation,
(C) Standing stubble being cleared from furrow , (D) Cleared furrow with 2-m buffer

It should be noted that furrow irrigation water will be slowed substantially by standing wheat stubble in furrows, resulting in increased infiltration and, in most cases, reduced application efficiency. In addition, some problems can occur, particularly in clay soils, with waterlogging.

This may be overcome by retaining the stubble in the furrows only until the start of the irrigation season. At this point, except for a 1-4 m buffer of standing stubble in the furrows at the tail drain end of the field, the point of a sweep is run through the furrow to clean out the stubble from the bottom 10-cm. This facilitates water flow through the field. The retained buffer is sufficient to slow water flow just enough to sediment out dispersed clay. Excess salts and nutrients adsorbed onto clay particles are deposited in the furrow and do not move off field with runoff. Figure 2.10.9 describes this operation.

Using cereal rotation crops to "sop" up excess nutrients leached out of the cotton root zone

Cereal crops can extract excess nutrients, particularly nitrates, which have been leached below the cotton root zone. The N taken up by the cereals are released on decomposition of the wheat stubble during the following cotton season. Efficiency of N uptake is improved by fertilising the wheat crop, as this improves wheat root growth and allows the root system to extend into the deeper soil horizons (Fig. 8). Figure 8 shows that root density of fertilised wheat is higher than that of either unfertilised wheat or grain legumes. As an example, at the bore-irrigated site described in Table 1 a wheat crop sown after cotton in May 2001 and fertilised with 60 kg N/ha as urea extracted 113 kg of N/ha from the depths below 60 cm. The equivalent fertiliser (anhydrous ammonia) value of this N (assuming a cost of $700/t) was $96.50/ha.

Using constructed wetlands to improve water quality

Recent research has suggested that various water quality parameters may be altered through the design of on-farm water structures. For example, areas of vegetation, particularly in tail drains, can improve sedimentation and microbial breakdown of pesticide residues; but areas of open water are also important for pesticide breakdown by sunlight. A diverse range of structures such as open water storages and purpose built vegetated wetlands may be useful to improve water quality.

When considering these options, growers should be mindful of the effect of vegetation on hydraulic performance, as the capacity and velocity of flow in vegetated taildrains will be considerably less than in clean drains. Similarly, the industry storage guidelines advocate the removal of vegetation from on-farm storages as root activity in storage walls may lead to storage failures. Structures should therefore be designed for purpose, whether this is storing water, transporting water or improving water quality. Further information has been recently published in the Australian Cotton Water Story (page 99).

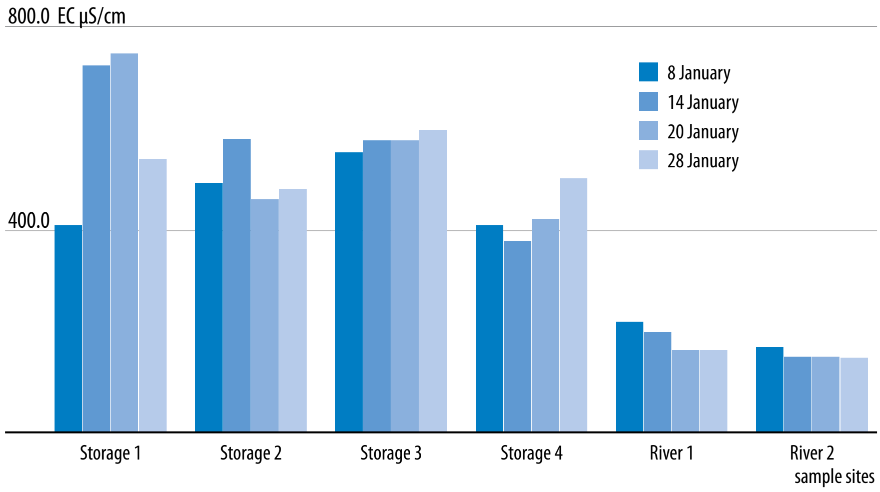
Case Study – Water Quality Monitoring at Dirranbandi

This case study shows the variability detected in water quality over a six week period in the 2001/02 summer at Dirranbandi. Water samples were collected from four on-farm storages (labelled S1 to S4) throughout the Dirranbandi district and from two sites along the Balonne River (labelled R1 and R2), one upstream and one downstream of Dirranbandi. The nutrient and salinity levels of these irrigation water samples were analysed.

Salinity

The salinity level of the Balonne River, measured by electrical conductivity (EC), was much lower than the on-farm storages and remained relatively constant (Figure 2.10.10). The lower electrical conductivity for the river may be explained largely by the fact that EC has a significant negative association with flow. This means that a flow in the river results in the dilution of ions in solution, thus decreasing the EC.

Figure 2.10.10. Electrical conductivity of storage and river water



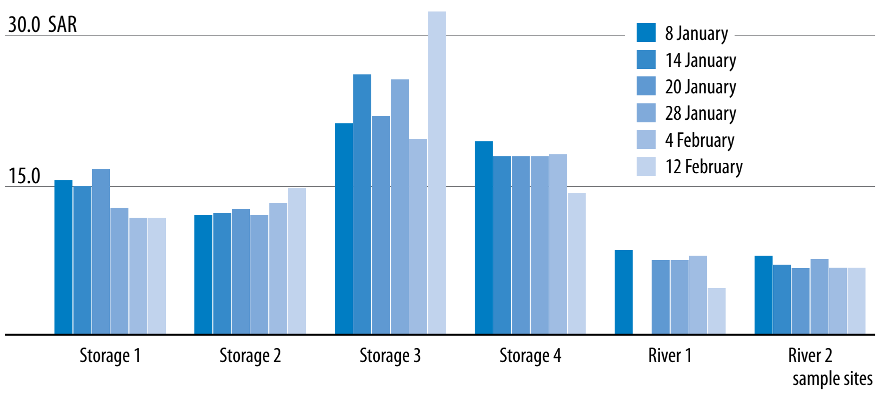
Differences in the storages can be largely explained using recent soil tests from the farm. The sodium and calcium content of the soil on one farm is almost double that of the others. The majority of the samples (91%) were classed as a very low (<650 µS/cm) salinity hazard for irrigation water according to national water quality guidelines, indicating that the water is suitable for irrigation of sensitive crops and will pose no threat to soil salinity.

The average EC of the water in the Balonne River for both sample sites was 170 µS/cm, which is low relative to studies in other cotton-growing valleys that report ECs between 306 µS/cm and 1565 µS/cm in the Liverpool Plains (Wood 1997), 227 µS/cm and 1626 µS/cm in the Gywdir (Montgomery 2002), and up to 800 µS/cm in the Namoi River (DLWC 2001).

Sodicity (Sodium Adsorption Ratio)

The sodium adsorption ratio (SAR) is a measure of the proportion of sodium ions in the soil or water solution, relative to other cations (magnesium, calcium and potassium). The SAR of the river water is much lower than the on-farm water storages. The SAR of the storages varied with 42% of the storages falling in a high sodicity class (8-14) and 58% in a very high sodicity class (>14) (Figure 2.10.11). The difference between the SAR of storages is consistent with the soil test results, which explains why S3 had a much higher SAR value. Irrigating with sodic water will affect soil structure, resulting in soil dispersion and reduced water infiltration.

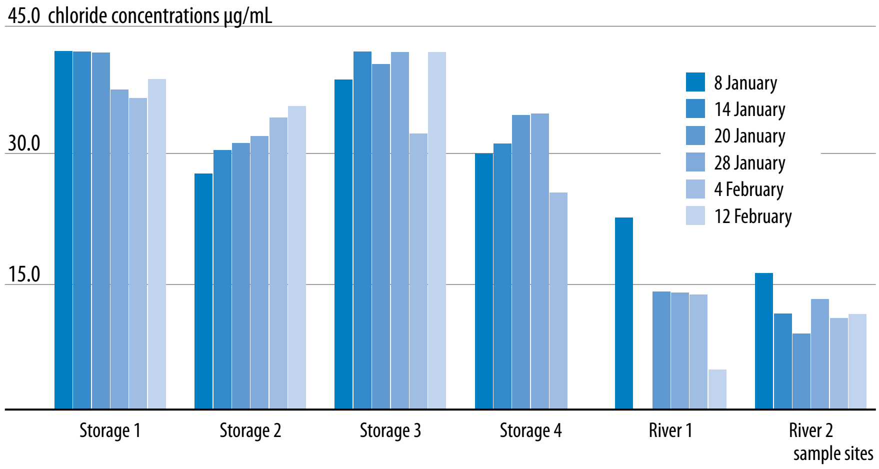
Figure 2.10.11. Sodium adsorption ratios of storage and river water



Chloride load

Chloride is essential for plant growth, although high levels of chloride can cause damage to the crop's foliage and increase the uptake of cadmium from the soil, which can be toxic. All samples had concentrations less than 175 µg/mL (Figure 2.10.12), which indicates that the water is suitable for irrigation of chloride-sensitive crops such as cotton. The chloride level in the river was almost half the values recorded throughout the Gwydir Valley by Janelle Montgomery (2002).

Figure 2.10.12 Chloride levels in storage and river water

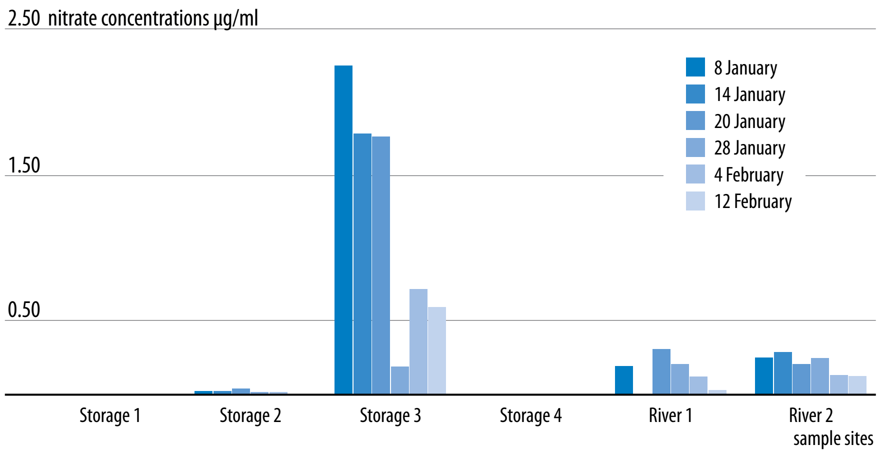


Nitrate load

Nitrate occurs naturally in water and is usually present in river water at concentrations below 1 µg/mL. Levels higher than this are generally related to the use of nitrogen fertiliser, manure, intensive livestock production or urban wastes.

The national guidelines for irrigation water suggest that nitrate levels in irrigation water should be in the range of 25 to 125 µg/mL. During the observation period, nitrate levels were below these levels (Figure 2.10.13). No nitrate was detected in Storage 1 or Storage 4, and only low levels in Storage 2. Storage 3 recorded a much higher nitrate level (2.25 µg/mL), which is a direct consequence of the addition of nitrogen fertiliser to the water prior to sampling.

Figure 2.10.13. Nitrate levels in the storage and river water



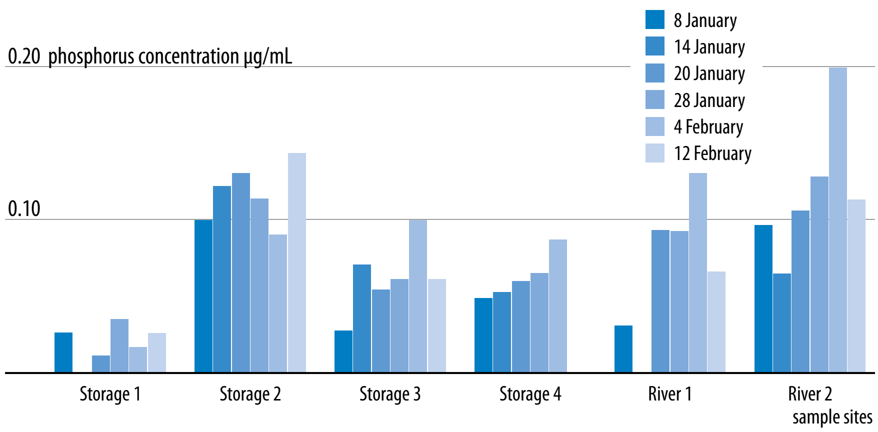
The two river sites recorded maximum nitrate values of approximately 0.3 µg/mL. These levels are similar to those presented from other water quality studies in cotton-growing regions. The majority of samples collected throughout the Gwydir Valley showed nitrate levels between 0 and 1 µg/mL (Montgomery 2002).

Phosphorus

Generally, the concentration of phosphorus in the river water was higher than that in the on-farm storages. This is because phosphorus binds tightly to sediment particles and there are often more sediment particles in river water (Montgomery 2002).

Figure 2.10.14 shows that Storage 1 had the lowest phosphorus concentration, while Storage 2 had the highest concentration. This pattern is consistent with soil test results from these farms. Using a Colwell P soil test, soil P levels of 2 mg/kg were measured on the Storage 1 farm compared to the farms of Storages 2, 3 and 4 which measured 36, 26 and 25 mg P/kg respectively. The levels of phosphorus in the river water increased during the sampling period.

Figure 2.10.14. Phosphorus levels in the storage and river water



High phosphorus levels in water do not generally affect plant growth although, if microbial activity is healthy, they may cause algal growth that may block irrigation equipment (Montgomery 2002). The majority (76%) of the samples from the storages and river exceeded the maximum standard of 0.05 µg/mL for irrigation water that has been set in the ARMCANZ guidelines.

The phosphorus levels in the Balonne River are comparable to other river systems within cotton-growing areas in Northern New South Wales and Queensland. Studies by DLWC have recorded median values of 0.1 µg/mL in the Narrabri Creek at Narrabri and 0.445 µg/mL in the Peel River at the Bective Reserve.

Action

This project highlighted that every on-farm water storage, even those within close proximity of each other, were different in terms of water quality. Monitoring the salinity of storage and river water using an electrical conductivity meter will give you an indication of the level of salinity in the water and any changes that occur over both the short and the long term.

It is very simple and inexpensive to measure the electrical conductivity of a water sample. It costs about $100 to buy your own meter to measure salinity levels.

For more information about monitoring the electrical conductivity or nutrient content of your irrigation water, contact your Cotton CRC Industry Development Officer.

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Section 3

Irrigation management of cotton

3.1 Cotton growth responses to water stress

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Key points

- Cotton plant responses to water stress will vary depending on the stage of growth at which the stress occurs, the degree of stress and the length of time the stress is imposed.
- The plant aims to establish a balance between carbohydrate supply and demand. Water stress at any stage of growth will impact on both the production and distribution of carbohydrates throughout the plant. Carbohydrate demands placed on the plant primarily by developing bolls restricts excessive vegetative growth.
- Through adaptation, the cotton plant survives during periods of water stress by prioritising the maintenance of different physiological processes to ensure the production of viable seed and therefore cotton fibre. The impact of water stress on final yield will depend on the degree to which each physiological process is affected.

By understanding some of the principles of plant growth and how cotton plants have adapted to reduce the impact of water stress on growth, growers may better utilise their available water resources to improve water use efficiency.

Plant growth = carbohydrate supply and demand.

Cotton has an indeterminate growth habit and therefore under favourable conditions the number of leaves, new nodes, fruiting branches and squares, can increase rapidly unlimited by a phenological time frame and will continue to be produced while conditions remain favourable. During the pre-flowering stages of growth, production of carbohydrates (through photosynthesis) is in excess of demands and as a result vigorous vegetative growth occurs.

As plant growth continues, the demands for carbohydrates by the component plant parts such as bolls increase, and production becomes limited by environmental conditions. Boll growth exerts large demands for carbohydrates and it is through the balance between boll demand and leaf production that vegetative growth is restricted. The over production of squares by the plant is an adaptation by the cotton plant which ensures that a balance is achieved between carbohydrate supply and demand. Square shedding during periods of cloudy weather for example are mediated through reduced carbohydrate supply and are examples of how plant growth is balanced between carbohydrate supply and demand.

Water stress can restrict both vegetative and boll growth. It has been shown that no matter what degree of water stress is imposed on a crop, the proportionality between vegetative growth and boll development remains relatively constant. Similar results have been achieved with crops receiving different amounts of nitrogen. This implies that independent of water or nutrient supply, the plant will always attempt to form a balance between vegetative growth and boll development.

Table 3.1.1 shows distribution of dry matter in cotton plants grown under different irrigation frequency and nitrogen fertiliser (average over three seasons data).

Table 3.1.1. Distribution of dry matter in cotton 140 days after sowing

Irrigation	Fertiliser kg N ha^{-1}	Dry weight of tops gm^{-2}	Distribution of dry weight (%)		
			leaf	stem	boll
Frequent	0	450	15	34	51
Frequent	150	747	15	42	43
Infrequent	0	460	18	34	48
Infrequent	150	695	18	39	43

Source: Constable and Hearn 1981

Carbohydrate production and water stress

Production of carbohydrates through the process of photosynthesis and their storage are the primary functions of leaves. Leaf age is an important plant factor affecting daily photosynthesis. In non-stressed plants, peak carbohydrate production from an individual leaf occurs when the leaf is around 20 days old. Peak plant carbohydrate production will occur when the combination of photosynthesis per unit leaf area and leaf area is maximised. In non-stressed plants this usually occurs some 60 to 70 days from the unfolding of the first true leaf (75 to 85 days after planting). Decline in daily carbohydrate production after this date results from increasing canopy leaf age and increased self shading and the increase in boll demand for carbohydrates, which restricts any new leaf development.

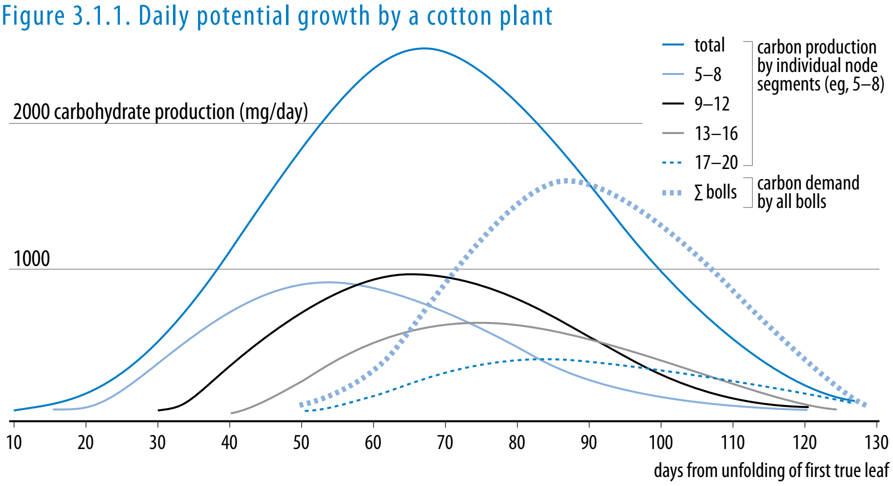
Figure 3.1.1 shows daily potential carbohydrate production for individual node segments and an accumulated total for the total canopy, boll demand has been superimposed over production.

It is evident from this data that factors which impact on leaf development, particularly early leaf development, will affect total plant carbohydrate production and therefore yield potential. Water stress has been shown to reduce whole plant leaf area largely through reductions in total leaf numbers. However the rate of leaf expansion is also reduced, which in turn reduces the size of individual leaves.

Reduction in leaf area will obviously impact on the level of total canopy photosynthesis. Photosynthesis is maintained in priority over leaf expansion and development. This allows the plant to maintain current photosynthetic capacity but limits future capacity. The value is that it also stops demand for water increasing when there is not enough to meet even current demands.

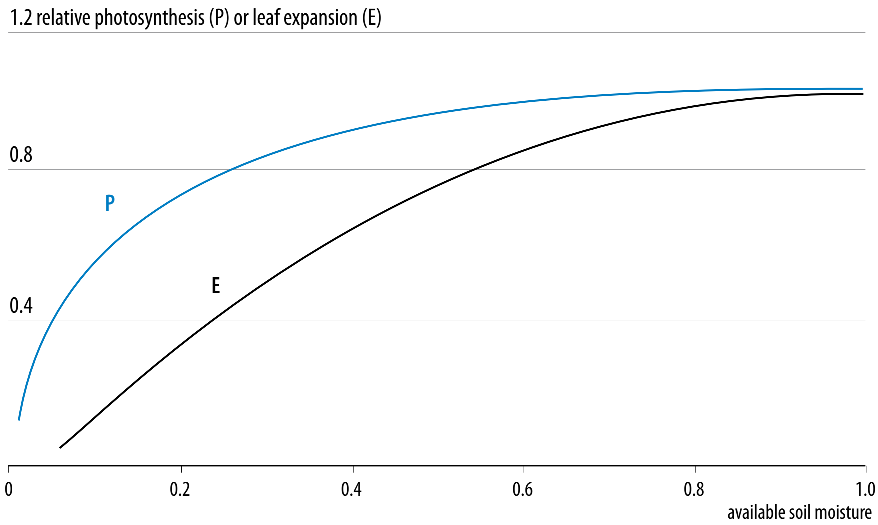
Figure 3.1.2 shows the relationship between available soil water and relative leaf net photosynthesis and daily leaf expansion.

Figure 3.1.1. Daily potential growth by a cotton plant



Source: Constable and Rawson 1980

Figure 3.1.2. Available soil water and its effect on relative net photosynthesis and relative daily leaf expansion



Relative refers to the ratio between stressed and non-stressed plants.

Source: Constable and Rawson 1982

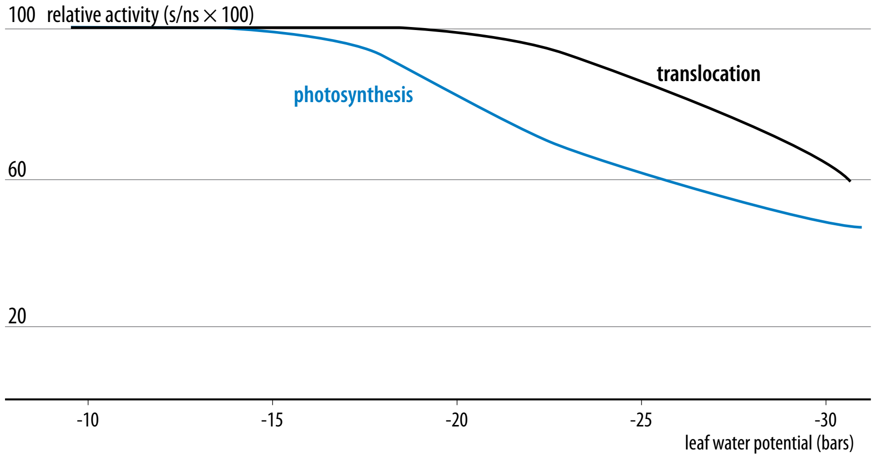
It can be seen that leaf expansion has been greatly reduced by the time photosynthesis has started to decline. In terms of plant growth, the maintenance of photosynthesis will enable boll and root growth to continue longer during periods of water stress than vegetative growth. This drought adaptation will also allow the plant to recover quickly from small periods of mild stress, particularly during early, pre-flower growth stages

Carbohydrate re-distribution

The export or re-distribution of carbohydrate from an individual leaf is initially small, so as to allow effective leaf growth. Once leaf growth has stopped at around 20 days of age, however, carbohydrate in excess to leaf requirements is produced and this can either be stored as starch for later use or be directly exported to actively growing plant parts.

The rate of export of carbohydrate from the leaves is determined by the demand imposed by other plant parts. Actively growing organs such as roots, bolls and growing terminals act as sinks which will actively compete for the available carbohydrate. The pattern of distribution will depend on the leaves capacity to satisfy the requirements of individual sinks. Since it is particularly important for the plant to have the capacity to utilize excess carbohydrate during periods of stress. plant adaptation allows the processes involved in transferring carbohydrates away from the leaves to continue at higher water stress levels than those that reduce photosynthesis (Figure 3.1.3). Therefore, water stress not only effects production of carbohydrate but also alters its distribution.

Figure 3.1.3. Relative activity of photosynthesis and translocation in cotton leaves as a function of leaf water potential



s = stressed; ns = non-stressed

Source: Krieg and Sung 1986

Root development

At the time of flowering, around 80% of the plant's root system may be developed and thus the root system imposes the greatest demand for excess carbohydrates during early plant growth. After flowering, boll development begins to compete with the root system for carbohydrates and the rate of root expansion declines. Under water stress, however, the plant is adapted to place priority on root growth. As a result, root expansion occurs at the expense of vegetative and boll growth. Figure 3.1.4 compares vegetative and root dry matter levels for crops produced with adequate moisture and moisture stress (dotted line).

Figure 3.1.4. Pattern of dry weight over time

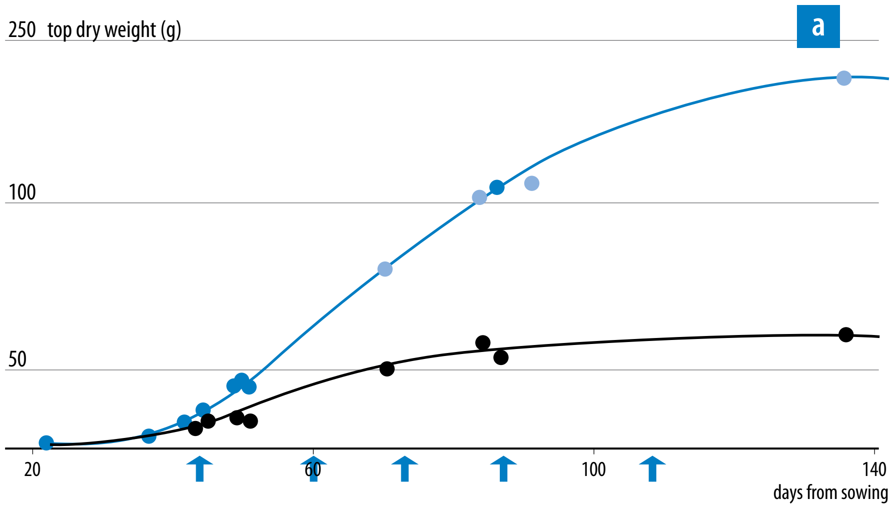
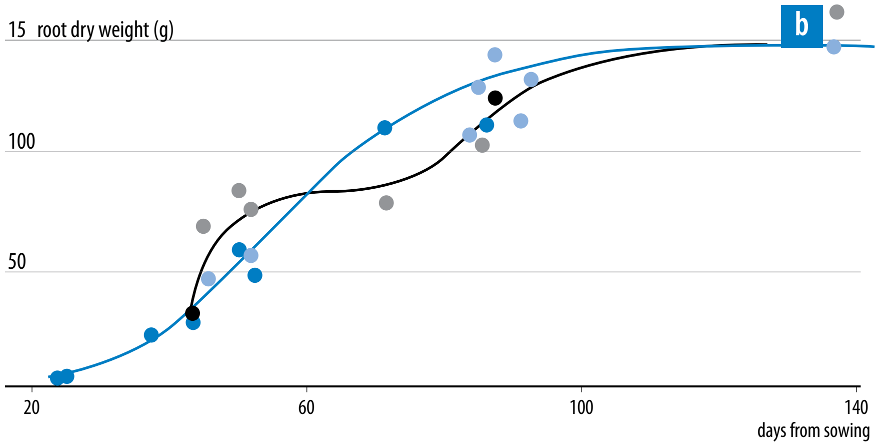


Figure 3.1.4. (cont.)



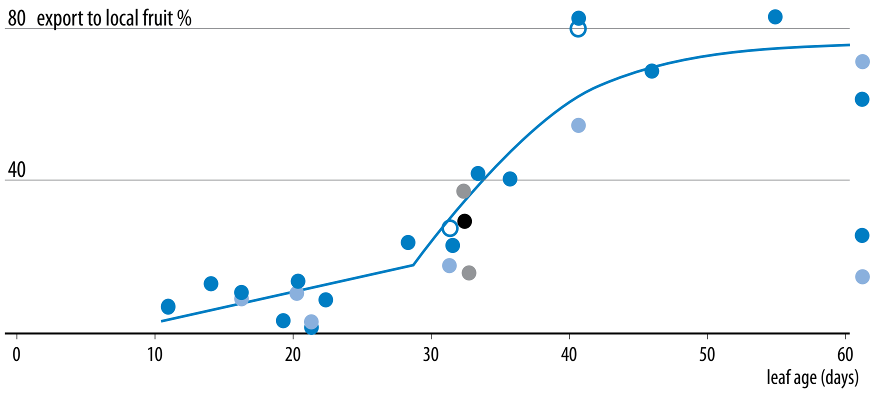
(A) top vegetative growth and (B) roots as affected by moisture stress.
Blue line = adequate moisture, black line = moisture stress

Source: Constable and Rawson 1982

Boll development

Squares exhibit little carbohydrate demand on the plant during early growth, with bracts supplying the majority of their requirements. A rapid increase in demand for carbohydrates occurs after flowering (Figure 3.1.5) This is the reason that the majority of fruit is shed as flowers and/or two or three day old bolls. Shedding of bolls can occur up to an age of 10 to 14 days, after which cell wall thickening between the boll and stem prevents an abscission layer from forming. In the case of a rapid onset of water stress, young bolls in which growth has stopped may be retained by the plant and appear as 'mummified' dry bolls. Figure 3.1.5 illustrates that up to 80% of the carbohydrate produced by this leaf is exported to the local boll. It has also been shown that the proportion of carbohydrate distributed from leaf to boll is not effected by water stress. This implies that boll development is affected by total carbohydrate supply and not by the rate of distribution from adjacent leaves. This is consistent with the fact that redistribution of carbohydrate can occur at stress levels beyond those that effect production (Figure 3.1.3) .

Figure 3.1.5. Relationship between leaf age and the proportion of carbon export from the leaf found in the adjacent fruit as affected by soil water

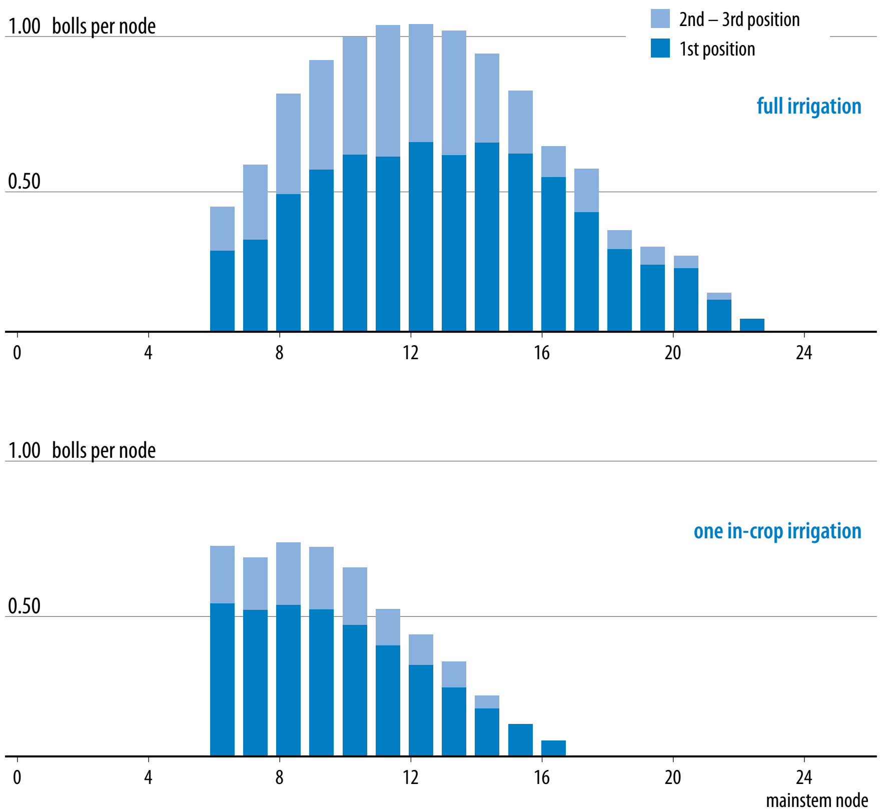


Source: Constable and Rawson 1982

As boll demand exceeds supply from the adjacent leaf, inter-boll competition for further carbohydrate occurs. Older bolls compete more effectively than younger bolls and this results in the movement of carbohydrates away from the extremities of the main stem and individual fruiting branches. Those bolls unable to compete effectively are either shed by the plant or are reduced in size hence the occurrence of smaller boll towards the top of the plant. It is for this reason that the majority of fruit, particularly secondary position bolls, are retained by lower fruiting branches.

In non-stressed irrigated crops, increased early vegetative growth results in shading of lower leaves and this causes reduced retention and boll size on the first two or three fruiting branches. The final results of this combined inter-boll competition and leaf shading in fully irrigated crops is the common bell shaped distribution of bolls throughout the plant (Figure 3.1.6). In the case of crops under water stress, the same inter-boll competition occurs, however there is generally less total carbohydrate to be distributed amongst bolls. Reduced vegetative growth also minimises shading of lower leaves, resulting in the higher boll retention and boll size occurring amongst the first fruiting branches. Figure 3.1.6 shows the differences in boll distribution throughout the plant that can occur between a fully irrigated crop and a crop that had received one in-crop irrigation.

Figure 3.1.6. Pattern of boll distribution as affected by water stress



Source: D Gibb and Colly Farms

Water stress and crop yields

The degree of plant response to stress will vary depending on the level of stress which occurs and the timing at which the stress is imposed, relative to crop growth. Table 3.1.2 summarises the plants responses to differing degrees of water stress, the effects on final crop yield, fibre development, maturity and water use efficiency are also discussed.

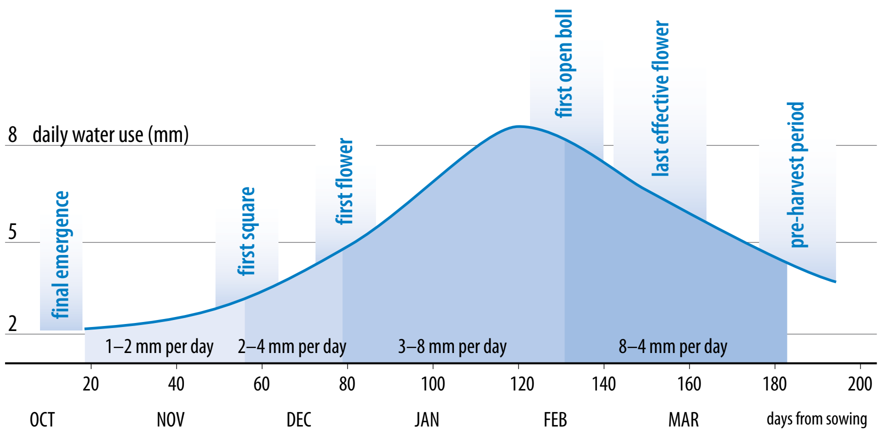
Table 3.1.2. Summary of responses to water stress

Degree of water stress	Possible causes	Physiological plant responses	Yield effects on maturity and WUE
Minimal stress	Reduced irrigation deficit	Excessive vegetative growth	Reduced yield
	Excessive rainfall	Increase in leaf area	Reduced boll size
	Cloudy weather	Extended flowering cycle	Delayed maturity
	Excessive early insect damage	Reduced carbohydrate surplus for bolls	Normal fibre length but low micronaire
	High plant stands	Reduced root development	Poor WUE
		High boll capacity but poor boll retention	
Mild stress	Optimum irrigation deficit	Optimum vegetative growth rate	Maximum yield
	Average temperatures (not excessively hot)	Leaf expansion restricted	High quality cotton
		Photosynthesis remains unaffected	No delay in maturity
		Maximum carbohydrate surplus	Maximum WUE
		Maximum boll development	
		Good fibre development	
Moderate stress	Increased irrigation deficit	Reduced vegetative growth and leaf expansion	Reduced yield
	Extremely hot temperatures with low humidity, windy conditions	Reduced photosynthesis	Early maturity
	Little cloud cover	Reduced surplus carbohydrates	Increased short fibre micronaire
		Reduced boll carrying capacity	Slight decrease in WUE
		Increased fibre development	
Severe stress	Less than 3 irrigations	Vegetative growth greatly reduced - stops after flowering	Low yields
	Dryland crops	Greatly reduced carrying capacity	Short fibre
		Little surplus carbohydrates	High or low micronaire depending on stress pattern
		Low boll retention	WUE depends on rainfall

Crop water use and plant growth

A cotton crop's requirement for water changes throughout the growing season, following the pattern of evapotranspiration. The rate of evapotranspiration is determined primarily by meteorological factors and the availability of soil water. Total crop evapotranspiration will vary with canopy size, or leaf area. Crop leaf area peaks some 3 to 5 weeks after the start of flowering and this results in a peak in daily water use of between 8 and 10 mm (Figure 3.1.7).

Figure 3.1.7. Nominal seasonal daily water use (mm/day) for cotton production



Maximum demand for water also coincides with the growth period between peak flowering and early boll development. Exposing the plant to water stress at this stage of growth can result in significant yield reductions. The impact of water stress at different crop growth stages on final yield is directly related to the water demands expressed by the crop. Stress during periods of high water demand can produce large reductions in yield. Table 3.1.3 shows yield reductions resulting per day of stress for different crop growth stages. Stress during peak flowering can double yield losses compared to early or late seasonal stress. The impact of any one stress period is increased if followed by further stress. For high yielding, Bollgard II crops the impact of water stress during late flowering can equate to a yield loss of 2.7% for every day that an irrigation is delayed.

Table 3.1.3. Yield loss (%) per day of water stress (extraction of > 60% plant available water) (Source Yeates et al. 2010#; Hearn and Constable 1984*)

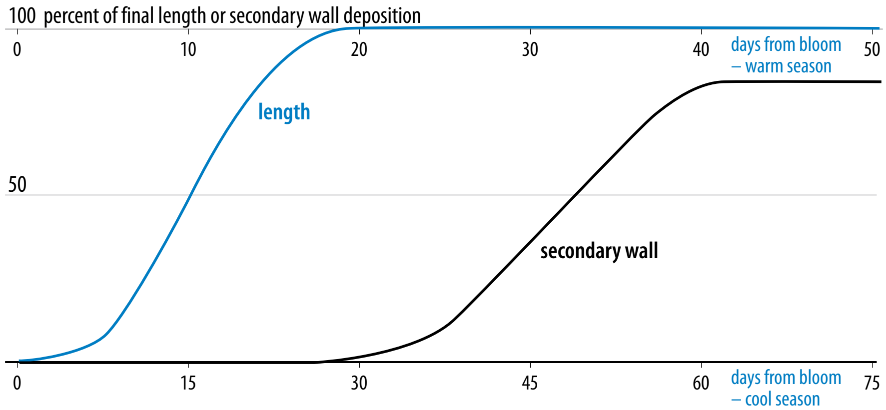
	Past Conventional*	Bollgard#
Squaring	0.8	1.1
Peak flowering	1.6	1.7
Late flowering	1.4	2.7
Boll maturation	0.3	0.69^

^ 14 d post cut out

Fibre development

Fibre development begins the day after flowering and is a two stage process with fibre elongation (length) preceding secondary wall development (thickening). In a non-moisture stressed situation, fibre length reaches a maximum between 20 and 30 days post flowering with fibre wall development being completed some 40 to 60 days post flowering, depending on temperature (Figure 3.1.8).

Figure 3.1.8. Time of biological maturation of cotton fibres as effected temperature



Although temperature is the main determinant of the length of the period between flowering and boll opening, carbohydrate supply directly effects the degree of fibre development and final boll size. As discussed previously, under water stress younger bolls are shed to enable the development of older bolls. The plant has increased its adaptation for survival during drought by placing priority on seed and fibre development over total fruit retention. This is demonstrated by the fact that young boll shedding can occur at lower moisture stress levels (-19 bars), while fibre development is not effected until higher stress levels (-26 bars) are reached. The increase in micronaire generally associated with cotton suffering from water stress at the end of flowering is a good example of this plant adaptation. Increase in micronaire occurs because younger bolls are shed, and more carbohydrate becomes available to lower bolls. With fibre development continuing under higher stress levels, any extra carbohydrate available is allocated to increases in fibre cell wall thickening, leading to increases in micronaire.

Moisture stress during peak flowering will tend to affect fibre length rather than fibre maturity, while stress later in the season will primarily affect fibre maturity.

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3.2 Managing irrigated cotton agronomy

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Key points

- Appropriate irrigation scheduling improves water use efficiency, reduces water-logging, controls crop canopy growth, improves the effectiveness of rain and allows better management of soil structural problems.
- Cotton is most susceptible to water stress during flowering until just after cut-out. Research has shown that yield losses can be up to 2.7% loss of yield per day of stress during this period in high fruit retention crops.
- If water stress occurs, it is better late or early in the season, but not in the middle, during peak flowering and early boll fill stages. When irrigation water is limited, save water for the flowering period.
- The best approach to determining when to irrigate is to use a combination of plant visual symptoms, crop growth and development monitoring, measurements of available soil water and weather forecasts to predict when irrigation is required.
- To optimise yield potential and water use efficiency in cotton it is important to balance growth by matching nitrogen application and irrigation scheduling to crop requirements.
- Mepiquat chloride can be a valuable tool to check growth if it becomes too vigourous.

Irrigating cotton requires balancing excessive vegetative growth due to abundant water supply against limited yield potential due to water restriction. Correct agronomic management and irrigation scheduling improves water use efficiency, reduces water-logging, controls crop canopy growth, improves the effectiveness of rain and allows better management of soil structural issues.

This WATERpak topic explains how to optimise the management and irrigation scheduling of cotton. WATERpak Chapter 2.1 provides an overview of evapotranspiration, soil moisture and irrigation scheduling techniques as may be applied to any crop. WATERpak Chapter 2.7 discusses how to calibrate soil water based measuring devices and determine plant available water content (PAWC) whilst WATERpak Chapter 2.3 describes tools that can be used for irrigation and crop management.

There are a number of factors to consider when scheduling an irrigation including;

- Total water availability (WATERpak Chapter 2.2)
- Limited water situations (WATERpak Chapter 3.3)
- Crop growth status and potential yield (WATERpak Chapter 3.1)
- Future rainfall and future temperatures
- Practical farm management logistics such as the physical movement of water
- Current soil water content (WATERpak Chapter 2.1)

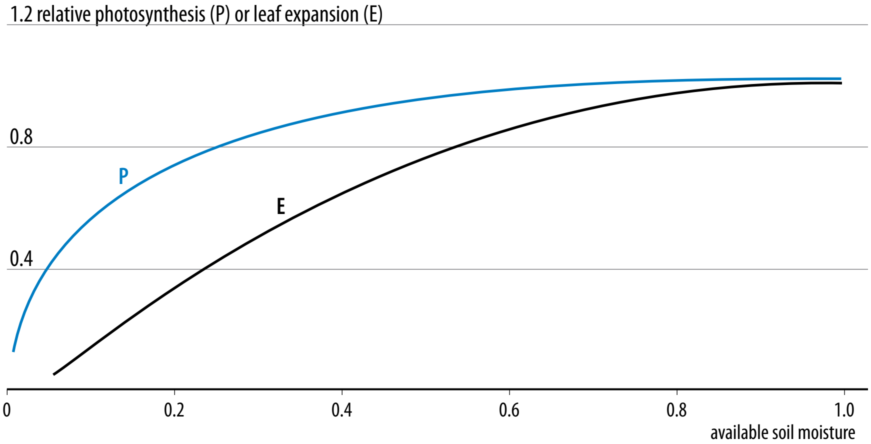
Whilst this chapter is primarily focussed on furrow irrigated systems, some discussion of scheduling under alternative systems (CPLM and drip) is also included.

Water use by cotton plants

Plants lose water through their leaves to keep cool and to move nutrients around the plant. They need to absorb water from the soil to replace what they have lost. This phenomenon is more severe over the hot summer months, as more than 95% of water used by the crop is for cooling itself. Photosynthesis is very sensitive to leaf temperature which the plant regulates by the movement of water through the leaf in a similar way to how perspiring cools humans. Water is also important for photosynthesis, cell expansion, growth, nutrient supply and turgor pressure (prevents the plant from wilting and controls stomatal opening).

Figure 3.2.1 shows that water deficit reduces cell expansion, which is observed by agronomists as reduced leaf expansion and stem elongation. Greater levels of water stress cause a decline in net photosynthesis and further reduce cell expansion. Photosynthesis is the process by which plants use CO_2 from the atmosphere to produce carbohydrates (assimilates) to support boll growth and fibre development. When the plant senses that moisture supply is becoming limited, vegetative growth slows and priority is given to boll development.

Figure 3.2.1 : The relationship between available soil water and relative leaf net photosynthesis (P) and relative daily leaf expansion (E). Relative refers to the ratio between dry and control plants.



Source: Constable and Rawson 1982

In descending order of sensitivity, Hearn (1994) summarized that water stress firstly reduces leaf expansion, then organ production (leaves and sites), then fibre length, then photosynthesis, then boll retention, then fibre thickening and finally root growth and function. Like many crops, cotton is most sensitive to water stress during peak flowering. Stress during peak flowering and boll filling is likely to result in double the yield loss compared to stress during squaring and late boll maturation (Table 3.2.1).

The extent of the yield loss will vary with circumstances. Yeates et al. (2010) found that Bollgard II cotton cultivars are more sensitive to water stress near cut-out flowering with a yield reduction of 2.7% per day of stress compared to 1.4% reported for non-Bollgard II cultivars in the past (Hearn and Constable 1984) (Table 3.2.1). This is because Bollgard II cultivars have higher fruit retention early in flowering and therefore a much higher boll demand for assimilate late in flowering.

Table 3.2.1. Yield loss (%) per day of water stress (extraction of > 60% plant available water)

	Past Conventional*	Bollgard#
Squaring	0.8	1.1
Peak flowering	1.6	1.7
Late flowering	1.4	2.7
Boll maturation	0.3	0.69^

^ 14 d post cut out

Source Yeates et al. 2010#; Hearn and Constable 1984*

Water logging can cause yield losses as great as those experienced by water stress. For example, Hodgson (1982) reported yield losses of up to 2.4 % per day of stress due to water logging and low soil oxygen levels. Cotton's symptoms and responses to water logging are discussed in WATERpak Chapter 3.4 .

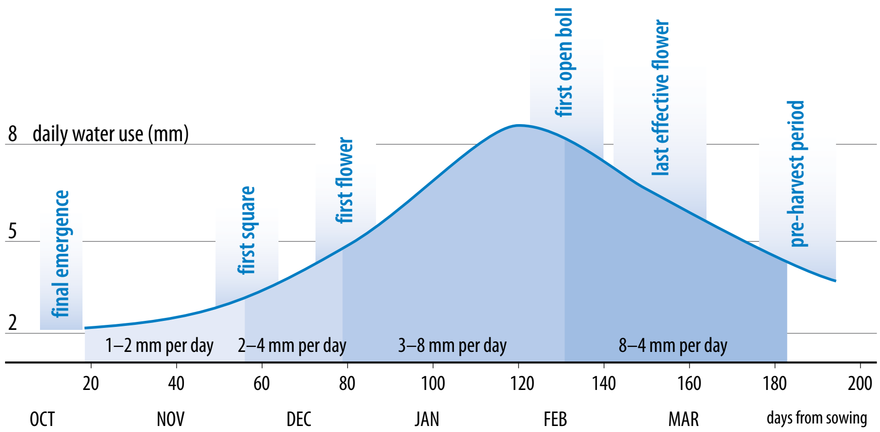
Seasonal and Daily Crop Water Requirements

Research and field trials show that to obtain maximum yields, cotton crops need to use on average about 700-750mm (7-7.5 ML/Ha) of water. This can come from rain, stored soil moisture and irrigation during the season (see WATERpak Chapter 2.1 for further explanation of crop water use (ET_c)). This figure will be less in shorter season areas.

The amount of water used is the sum of the evapotranspiration (leaf transpiration + soil evaporation), which is driven primarily by meteorological factors of solar radiation and air temperature and the crop's leaf area. As leaf area, radiation and temperatures increase during the season, so does the demand for water. The peak flowering and early boll development stages see increasing demand by the crop to fill bolls and are also the periods where crop growth rate is highest. Hence maximum demand for water occurs at this time.

This is demonstrated in Figure 3.2.2, which shows how the daily crop water needs vary with temperature and stage of the crop. Early in the season, the cotton plant's water use will be 2 to 4 mm per day, which will rise to a peak of 8 to10 mm per day in late January. The daily water use drops to about 5mm/day in March. By studying your own daily water crop figures it is possible to plot your own curve like the one in Figure 3.2.2.

Figure 3.2.2. The daily water use of cotton plants



Determining irrigation requirements

The optimum irrigation strategy for cotton in furrow irrigated systems has been well studied in Australia. There is no single strategy that will provide the optimum irrigations every year. The best approach to determining when to irrigate is to measure available soil water, take note of plant visual symptoms, monitor crop growth stage, and make use of weather forecasts to predict when irrigation is required.

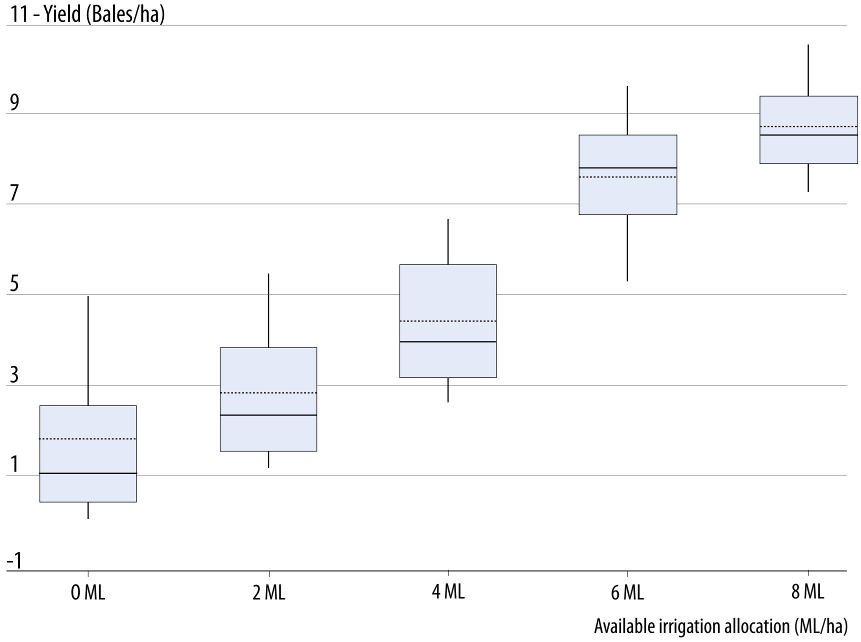
The widespread adoption of two gene transgenic Bt cotton (Bollgard II) cotton varieties has meant that management practices (including irrigation scheduling) have been re-examined in Australia and elsewhere. As a consequence of the improved insect control, early tipping of the terminal is minimal and the retention of squares (flower buds) and young bolls (fruit) is significantly higher in Bollgard II varieties when typical insect pest numbers occur. Higher retention of early fruit in Bollgard II cotton varieties creates a higher demand for assimilates earlier in the season and hence Bollgard II crops can be more sensitive to stress compared to crops with lower fruit retention.

Timely irrigation is more critical in Bollgard II crops particularly during flowering and at cut-out compared to crops with lower fruit retention and tipping. Ensuring adequate water availability is important to ensure adequate assimilate supply so that vegetative growth is not suppressed in preference to boll growth during early boll fill. An advantage of the rapid boll development of Bollgard II crops is earlier maturity and less seasonal water use than conventional varieties in seasons with typical pest numbers.

Seasonal irrigation requirements for individual locations can be estimated using tools such as CottBASE or CropWaterUse. CottBASE is also able to predict the production risk that might be associated with different management options or seasonal conditions (e.g. SOI).

For example, Figure 3.2.3 shows an example of the predicted yield for five different irrigation allocation scenarios at Narrabri. A range of parameters such as nitrogen application, target deficit and plant available water content (PAWC) can be modified to represent individual conditions. Further information on these tools is available in WATERpak Chapter 2.3 .

Figure 3.2.3 – CottBASE predicted yield for different irrigation allocations for an example farm at Narrabri .



Choosing a target soil moisture deficit

For furrow irrigated cotton, the best target deficit to avoid plant stress in average conditions is to aim for a deficit of approximately 50% of the plant available water content (PAWC). This is conservative for heavy clays and at times it may be possible to dry them to a 60% deficit without penalty. However, under conditions of high evaporative demand (very hot and dry conditions or hot winds) the target deficit as percentage of PAWC needs to be reduced because the stress occurs more rapidly and the crop can't adjust its growth and metabolism quickly enough.

It is also possible to infer an appropriate target deficit by interrogating continually logging soil moisture probes to estimate when the plant is about to stress. This process is discussed in detail in WATERpak Chapter 2.1. It is common for the target deficit to increase over the initial irrigations as the crop root zone expands. Recent work investigating the use of 'dynamic deficits' is discussed later in this chapter.

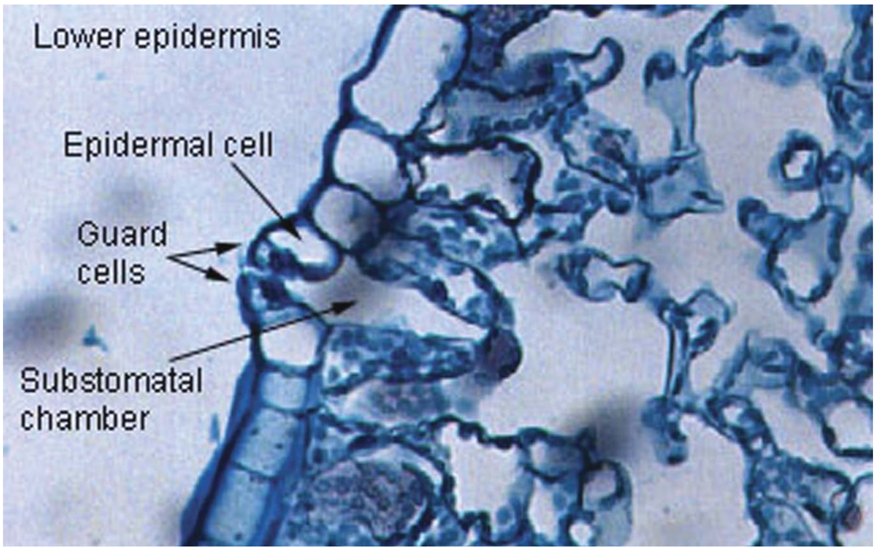
Crop monitoring

The cotton plant exhibits many plant water stress symptoms that can be used to help schedule irrigation. However, many of these occur after stress has occurred so the best approach is to anticipate crop requirements rather than to react after symptoms of water stress appear.

Visual symptoms of plant stress include;

- A change in leaf colour from a bright to darker green (almost blue colour when severely water stressed). It is most important to look at the health of the youngest leaves that are still growing in size.
- Plant wilting is an obvious water shortage symptom; however, care should be taken not to confuse a "midday wilt" with water stress. Midday wilt is an internal transport problem, which occurs when cotton plant roots cannot absorb water quickly enough to meet the plant's transpiration demand. Midday wilting occurs on very hot days; particularly when the air is dry. If the wilted plant recovers as the day cools down in the evening, this is a sign of "midday wilt" rather than a soil water shortage. Checking the soil moisture will help clarify any confusion. Due to its tropical origin, cotton, unlike many other plants, does not shut its stomates (Figure 3.2.4) in the heat of the day to conserve water. This allows gas exchange to continue and thus, the plant to keep growing at higher temperatures than many other crops. Only when severe stress occurs will the stomates respond and close. This usually occurs after leaf growth has stopped.
- Crops use water to keep cool so the leaves of water stressed crops are warmer to the touch. Around solar noon, crops that are not water stressed will be about 4 degrees Celsius cooler than the surrounding air temperature. Water stressed crops will be less than one degree cooler than the air temperature.
- The number of nodes (branches) above the most recent white flower on the first fruiting position is another plant observation used by cotton growers to schedule irrigations. Crops with more **nodes above white flower (NAWF)** generally have more vigour and this can be used to help decide which crops should be watered when water is scarce. When water availability is good irrigation should be used to extend the flowering period as long as possible to match the available season length. The change in NAWF each week is a guide to when irrigation may be required to continue node production and hence new squares. Assuming fruit retention is maintained, the longer NAWF takes to go below 5 the better.

Figure 3.2.4: Stomates on cotton leaf surface where $C0_2$ enters the leaf for photosynthesis while water simultaneously exits the leaf



Source: G Roth

Besides soil moisture, crop development is one of the most important things to monitor to determine crop water requirements. Keep a check on squaring nodes, first position retention and NAWF. Use the Crop Development Tool on the CottASSIST website to help keep track of how the crop is progressing.

A cotton plant, when not stressed, grows in a predictable way, which allows its crop development to be predicted using daily temperature data (day degrees). The Crop Development Tool (CDT) allows crop managers to monitor both vegetative and reproductive growth of their crops compared to potential rates of development. Monitoring your crop will enable you to use this information as a prompt to further explore why the crop may or may not be on track, and manage the crop accordingly. For more information refer to WATERpak chapter 2.3.

Crop management

A wide range of management factors can impinge on the water use efficiency of a crop. Insect management and soil structure are two major considerations and are covered in detail in the publications Integrated Pest Management Guidelines for Cotton Production and SOILPak. In addition, nitrogen uptake is linked to the amount of plant available soil water and mepiquat chloride can provide a management option to slow excessive crop growth. Both are discussed in further detail here.

Nitrogen impacts on water use

Approaches to the assessment of nitrogen requirements are spelt out elsewhere, in particular in NUTRIpak. The optimum amount of nitrogen application before sowing is by and large determined by soil type and the nitrogen status of the soil. However there is a strong interaction between fertilizer application and the amount of water applied.

Excessive nitrogen fertiliser can negatively affect crop growth. When adequate water is available, high rates of nitrogen can promote vigourous vegetative growth. The primary effect of the more vigourous growth is to result in a higher rate of transpiration. Except for when the soil is wet to the surface, the rate of evapotranspiration from the crop is governed by the leaf area index (LAI); that is, the leaf area per unit ground area.

Vigourous crops have more and larger leaves and thus a higher LAI. This means that the rate of water consumption per day is higher in crops that have received high rates of N and water. This extra growth and water consumption may or may not lead to commensurate improvements in yield. Where good retention is achieved and there is adequate season length, strong growth will lead to high yield. However, the greater canopy size may instead lead to a reduction in retention due to shading of the lower leaves and fruit.

In tropical or sub-tropical conditions the combination of high water, high nitrogen and high temperature can trigger the "rank growth syndrome". This is induced when high growth results in the shedding of fruit which in turn results in a lower carbohydrate demand by the fruit and hence there is more available for vegetative growth and thus there is continued vegetative vigour. The result is a large late crop with a possible reduction in yield.

A similar situation occurs in short season areas when too much nitrogen is applied. While the classical 'rank growth syndrome' may not be induced, the added vigour of the crop and delayed maturation of the crop may result in yield loss if the crop is truncated by cold weather. In either case, water consumption can be increased with little benefit in terms of yield, and possibly negative effects on yield.

If excessive nitrogen is unintentionally applied, the temptation is to apply water at the rate that the more vigourous crop demands it. This is not necessarily the best option. A slightly restricted water supply will reduce the vigour and reduce the overall risk of delayed development. The condition can also be dealt with by monitoring the vegetative vigour of the crop and using mepiquat chloride as required.

At the other extreme, when water is limited, the crop is less responsive to applied nitrogen, simply because growth is limited by water stress. The water limitation causes a reduction in leaf area and overall growth rate. There is therefore less need for nitrogen to build these structures. High rates of nitrogen resulting in vigourous growth in limited water situations can lead to higher early water use, leaving less water availability for reproductive growth later in the season. Thus, in limited water situations the crop is likely to require less applied nitrogen.

Waterlogging reduces nitrogen uptake. There appears to be two mechanisms: firstly the ability of cotton's roots to extract nitrogen from the soil is impaired and secondly, the amount of nitrogen in available forms in the soil is reduced because of the chemical reactions that take place in the anaerobic soil. The application of foliar nitrogen prior to waterlogging may prevent part of the yield loss in certain circumstances but it cannot fully compensate for the impact of waterlogging (See NUTRIPak for more details).

Nitrogen and water management can be particularly important in CPLM and drip systems which can supply water with neither the stress of waterlogging nor the small amount of stress that might occur just before a furrow irrigation is applied. Fortunately, the precise control of water under these systems may provide some flexibility to manage soil moisture deficit and moisture stress, as discussed later in this chapter.

Mepiquat chloride as a tool for managing excessive growth

Mepiquat chloride (MC) or Pix© suppresses the expansion of vegetative organs. During fruit growth, this may reduce the within plant competition between bolls and leaves for the available carbohydrate. The outcome can be a shift in the partitioning of dry matter to the bolls. However there is little evidence for this being a significant benefit in crops sown at normal times where water and nitrogen are well managed. In these situations, no yield advantage has been demonstrated and any advantage in dry matter partitioning disappears by maturity as the crop moves back to its inherent pattern of partitioning. Application of MC when the crop does not require it can lead to yield loss as it reduces crop growth.

MC is an advantage where a crop has become too vigourous. In this situation the suppression of leaf expansion and the subsequent shift in partitioning bring the carbohydrate supply and demand back toward the optimal balance. Interrupting the ongoing expansion of the crop also reduces the subsequent water usage. The outcome of these two responses mean there is the potential for both increased yield and increased water use efficiency.

It should be noted, of course, that reduced water or nitrogen availability will also control leaf expansion. The most efficient way to reduce the risk of excessive vegetative growth becoming a problem in the first place is correct nitrogen fertilisation and careful irrigation management. This will not cover every eventuality and the use of MC will be required from time to time when growth becomes excessive. This pattern of growth may occur in warm production areas or late sowings, after heavy insect damage or unfortunately timed rainfall events which have "released the brake" on the plant through shifting conditions in favour of vegetative growth.

The best approach to balance growth and optimise yield potential and water use efficiency is to:

- monitor your crop growth and development;
- apply nitrogen fertiliser based on soil tests, petioles or cropping history;
- monitor internode lengths to determine whether MC is necessary; and,
- carefully schedule irrigation to match crop requirements.

General rules for irrigation scheduling

The optimum irrigation strategy for cotton has been well studied in Australia. Whilst there is no single strategy that will perform optimally every year, there are a number of key decision points in determining an irrigation scheduling strategy appropriate for the situation at hand:

- decide whether to pre- irrigate or water up at sowing;
- determine when to apply the first irrigation;
- choose a target deficit to minimize stress during flowering and cut-out (see above); and,
- aim to dry the soil down to about 70% of PAWC by the time the crop has 60% bolls open.

Irrigation at sowing: pre-irrigate or water up?

The decision for a cotton grower to pre-irrigate or water up furrow irrigated fields is, like so many others, a decision that has to be made specifically to suit a farm. In certain situations it may also be necessary to combine the two options by pre-irrigating to plant into moisture and then giving the crop a "quick flush" to ensure good plant stands. Every farm is different and the following questions need to be considered before making a decision:

- What method has traditionally given the best plant stands and early vigour?
- What is the most efficient way to store my water, in an on farm storage or in the soil?
- Do I have enough water available or do I need to scratch for the last little bit?
- Is my cotton grown on a "warm" or "cold" soil?
- Does my cotton traditionally have a lot of pressure from seedling disease?
- How will my water account or carry over rules impact on water availability?
- What is the likely rainfall pattern before and after planting?
- Am I likely to get enough rain before planting to plant into moisture?
- Is it likely to rain straight after flushing up?
- Do I often have herbicide damage problems?
- Is my soil likely to dry out quickly before planting?
- Is my planter set up for dry or moisture planting?
- Are the beds even enough to get uniform moisture levels after harrowing to seek moisture?
- How does my soil soak up and how badly does it erode?
- Can I apply a small amount during a flush and not be wasteful?

The likely advantages & disadvantages of the different options are summarized in Table 3.3.2.

Table 3.3.2. Advantages & disadvantages of the different options for the first irrigation (furrow irrigation fields).

Pre-irrigation	Watering-up	Pre-irrigation and late flush
Likely advantages:		
No time pressure to apply the water	Potential to take advantage from pre-plant rain events, so the irrigation may require less water	Helps in fixing up plant stand problems
In a heavy clay, water losses can be less than keeping it in an on-farm storage	Easier to plant, especially when beds are not 100% even	Can give the crop the necessary "Boost" to get going after a slow start
Soil temperature is less likely to drop after planting - potentially less disease pressure	Faster planting operation and less machinery needed	
Likely disadvantages:		
Soil drying out too quickly	Reduction in soil temperature after planting in cool conditions, cool and wet soils can result in higher disease pressure	Likely to use more water
Dry rows in uneven fields	Herbicide damage more likely	
Soil stays too wet when followed by rain	Sides of beds might erode when flushing for a long time	
Unable to capture rainfall before planting	Can germinate weeds at the same time as the crop	
	Water logging if rain occurs after flushing	

Source: S Henggeler

Scheduling in-crop Irrigations

Optimising in crop irrigations is a balancing act for cotton; the aim is to provide sufficient water to prevent plant stress but not excessive water to ensure vegetative and fruit growth is balanced. It is important to tailor your irrigations to meet the needs of your crops to optimise yield and water use efficiency. Like many crops, cotton has stages of development at which it is particularly sensitive to stress (Table 3.2.1). Irrigation scheduling should strive to avoid exposure to stress during flowering and early boll filling stages. High boll load early in flowering can lead to premature cut-out and lower yields.

First in-crop irrigation

The first irrigation plays an important role in setting up for plant growth, fruit retention, fibre quality and boll weight. It requires a balancing act of not stressing the crop while ensuring water stored in the soil profile is fully explored by the cotton roots. The timing of this irrigation will vary depending on seasonal conditions and in crop rainfall.

Irrigating too early can lead to waterlogging. However, delaying the first irrigation will place the plant under stress and it is difficult to re-start a crop growing again if water stress has stopped growth. Under average conditions, many crops grown in heavy clay soils may not need irrigating earlier than halfway between squaring and flowering.

The demands of high fruit retention and absence of early main stem tipping afforded by Bollgard II® cotton mean that moisture stress prior to flowering may prevent canopy development and the plant may be too small to support the high early boll load. Recent research by Marcelo Paytas has shown for Bollgard II crops that when conditions are hot and dry and available soil water depletion in the root zone is at least 50%, irrigation up to 2 weeks prior to flowering will increase yield by 14 to 35% (Paytas et al. (2008, 2009).

Things to monitor or measure when scheduling the first in-crop irrigation:

1. Close examination of root extraction patterns and daily water use using soil moisture data is the best way to monitor the crops water status.
2. Monitoring fruit retention, changes in crop height and node number is essential to anticipate the need for water to increase canopy size (Crop Development Tool).
3. Check weather forecasts before irrigating; cool or wet weather near the time of the first irrigation can be detrimental to crop growth and water use efficiency

Subsequent Irrigations

Once regular irrigation has started, extending the interval between irrigations without monitoring soil water levels can result in significant yield reductions. Water can be saved, but yield losses will occur. The other consideration is that by stretching the irrigation interval, greater amounts of water will be required to fill the profile at the next irrigation and this can have efficiency implications.

For all irrigated cotton crops, water stress should be avoided during peak flowering and early boll fill stages. For Bollgard II cotton, high fruit retention means that crops are most susceptible to water stress late in flowering and at cut-out (see Table 3.2.1). When irrigation water is limited, it should be saved for the flowering period as it is better if water stress occurs late or early in the season, but not in the middle.

In hot dry summers it is better to be early than late. Yeates et al. (2010) near Wee Waa found irrigating high retention Bollgard II at smaller deficits (40-50 mm deficit or 6 to 7 days) in hot, dry conditions during flowering increased yield by 17% and CWUI by 8%. Irrigation scheduling based on small deficits requires skill and a system that can apply water quickly. Otherwise application efficiencies will be lower and the crop may be more susceptible to waterlogging.

Conversely, in summers when the air is more humid and with storm events, there may be some room to stretch irrigations intervals providing that the plant is not under stress. Experiments showed where mild growing conditions (higher in-crop rainfall and less evaporative demand) were experienced, scheduling irrigations to a greater deficit (80 mm) maximised yield and WUE, by allowing the opportunity to capture more in-crop rainfall rather than irrigating at a small deficit.

For high yielding (>12 bales per ha) crops with high fruit retention and a main stem that is not tipped, the plant must have enough vigour to grow bolls from squares produced on the top of the plant and on outside positions on fruiting branches (Table 3.2.3). All fruit compete for resources and any moisture stress will be a signal to the plant to favour the early bolls and not produce new squares or bolls. This is why water stress must be avoided during flowering in high fruit retention Bollgard II crops. Table 3.2.3 shows irrigation needed to be more frequent in the 2006/7 season because it was hot and dry while the 2007/8 season was milder and wetter so the plant was less stressed and could maintain photosynthesis with less frequent irrigation (i.e. with a larger soil moisture deficit).

Table 3.2.3. The importance of avoiding water stress during flowering. Shown is the effect of irrigation deficit on yield (b/ha) from squares present at 1st flower (1 flower/m) and yield on squares grown after first flower.

2006/7			2007/8		
Deficit (mm)	Yield from squares at 1st flower(bales/ha)	Yield from squares set after 1st flower (bales/ha)	Deficit(mm)	Yield from squares at 1st flower (bales/ha)	Yield from squares set after 1st flower (bales/ha)
39	6.3	6.0	35	5.7	7.3
68	6.3	4.4	54	6.4	7.4
82	6.3	4.2	78	5.9	6.7
124	4.2	1.9	126	6.2	5.8

Source Yeates et al. 2009

Careful monitoring of soil moisture extraction graphs, daily water use and crop development and growth will enable the correct timing of irrigations. Monitoring fruit load and crop development will also help in anticipating crop requirements. Soil moisture monitoring will indicate when the soil water levels reach the target deficit/refill point.

If irrigation is not applied prior to this point, then a yield reduction will occur depending on the stage of the crop. It should be noted that in circumstances when plant water requirement is very high (high wind and temperature combined with low humidity), plants can be stressed before the predicted soil water refill point is reached. To avoid yield loss in this case, irrigation should be scheduled early for Bollgard II crops during flowering.

The final irrigation

The prime objective of the last irrigation is to ensure that boll maturity is completed without water stress. At the time of last irrigation all bolls have been set, vegetative growth is limited and the majority of carbohydrates are used to satisfy boll demands. Once a boll reaches 10-14 days old, the abscission layer to cause boll shed cannot form. It is for this reason that boll numbers are not significantly reduced by late water stress, although fibre development can be affected. Crops that come under stress prior to defoliation (60 to 70% open - 4 Nodes Above Cracked Boll), can suffer some yield and fibre quality reduction. The level of reduction obviously increases the longer the stress occurs.

End of season water requirements can be determined by estimating the number of days until defoliation and predicting the amount of water likely to be used over this period. By defoliation, plants can be allowed to extract past the normal refill point to around 70% of plant available water content, ensuring a dry soil profile for picking. For cracking clay soils, this may be around 125 to 150 mm of soil water. The number of days until defoliation can be predicted in two ways; by determining the date of the last effective flower (cut-out) or by counting the number of Nodes Above Cracked Boll (NACB).

The last effective flower method is useful as a forward planning technique for budgeting water requirements in advance. Good managers can optimise crop nutrition, irrigation and use of growth regulators to guide the crop towards a desired date for last effective flower.

The NACB method is useful for monitoring final irrigation requirements as the crop matures.

The procedure is as follows:

Step 1 - Gather Data on Crop maturity

Last Effective Flower Method

Determine the predicted or desired date of last effective flower (cut-out). The Last Effective Flower Tool on the CottASSIST website is most useful. The last harvestable bolls take 600 to 650 degree days to reach maturity. Depending on sowing date, regions and temperatures this can be approximately 50 to 65 days. Day degrees can be determined for individual locations using the Day Degree Calculator on the CottASSIST website.

NACB Method:

Determine the level of crop maturity by counting the Nodes Above Cracked Boll (NACB). This is the number of nodes (fruiting branches) from the last cracked boll to the last harvestable boll on the top of the plant. The crop can be safely defoliated after 60 to 70 % of the bolls are open. If a boll can be cut easily, it is presumed to be mature. The crop should not be defoliated until less than 2% of bolls are immature.

Defoliation generally occurs when NACB is equal to 4. At this stage the top boll will have reached effective maturity and defoliation can occur without risk of reducing yield and quality.

Step 2 - Determine the number of days until defoliation

Last Effective Flower Method

The CottASSIST website will provide the number of days between cut-out and defoliation.

NACB Method:

Days to defoliation = (total NACB – 4) x 3

It takes about 42 day degrees for each new boll to open on each fruiting branch. If warm, sunny conditions prevail this could be around 3 days per node, however, mild and overcast conditions will slow opening.

Step 3 - Estimate the average daily water use of the crop during this time.

Predict daily water use from recent soil moisture and ET_c data and predicted weather conditions. Alternatively, use online tools such as CropWaterUse.

The crop daily water requirement starts to drop once bolls start opening (Figure 3.2.2). The CropWaterUse tool estimates weekly water requirements for different crops using historical weather data.

Step 4 - Determine the total water requirement

total water requirement = days to defoliation (Step 2) x average daily water use (Step 3)

Step5 - Compare the total required water to the remaining soil water

current soil moisture deficit + total water requirement > 70% PAWC ?

If the sum of the current soil moisture deficit and the predicted water requirement from Step 4 is greater than 70% of PAWC, then irrigation will most likely be required.

Some examples of final water requirements are provided in Table 3.2.4.

Table 3.2.4. Example final water requirement calculations.

Last Effective Flower Method	Crop A
Predicted cut-out date (from CottASSIST)	04 Feb
Predicted days until defoliation (from CottASSIST)	62
Total Water Requirement (from CropWaterUse*)	**356 mm**

NACB Method	Crop B	Crop C
Total fruiting branches	13	13
% open bolls	25-30%	Zero
NACB	9	13
Days to defoliation (NACB=4)	(9-4) x 3 = 15	(13-4) x 3 = 27
Estimated daily water use until defoliation*	5 mm/day	5.8 mm/day
Total Water Requirement	**75mm**	**156 mm**

*The CropWaterUse tool can be used to predict water requirements using historical weather data and user defined crop growth patterns. Alternatively, daily water use can be estimated as done for Crop B and Crop C, by estimating daily water use and multiplying by the number of days.

Crop A needs 356 mm of water over the next 62 days. If the profile is currently full and the plant available water capacity is about 200 mm, the deficit could reach 140 mm (70% of 200 mm) by defoliation without detrimental effect. Therefore another 216 mm of water needs to be supplied by irrigation and rainfall. With a typical irrigation deficit of 90 mm for this example, at least 2 irrigations are required as well as 36 mm in rainfall. If no rainfall eventuated, crop progress would need to be monitored to see if a third irrigation were required.

For similar soil moisture conditions, Crop B requires 75 mm of water to finish it off. Therefore irrigation is not required as there is 140 mm of soil moisture available. Only irrigate if the rooting depth is constrained or evaporation is higher than that predicted when estimating daily water use. On the other hand, Crop C will most likely require one irrigation because the crop requires more than the allowable depletion of 140 mm (70 % of PAWC). Likely rainfall would need to be considered in any such decisions.

If the crop is one irrigation short, boll size will generally be reduced rather than there being any significant reduction in boll numbers. This will result in a yield reduction. Fibre quality may also be affected, for example reduced micronaire, although little effect on fibre length would be expected. If the crop is two irrigations short, boll numbers will be reduced. Provided the crop doesn't move into rapid stress, boll size may increase due to the shedding of smaller bolls (less than 10 to 14 days old). Fibre micronaire may be reduced on younger bolls. Significant yield reductions can occur especially in vegetative crops that stress prior to boll opening.

Recent research by Steve Yeates on Bollgard II varieties found stretching the irrigation interval to just one irrigation 21 days after cut-out (one irrigation instead of two after last effective flower) led to yield losses of 10 to 18 per cent if there was no rainfall and as little as 0 to 9 per cent if good timely rain (more than 40 mm) fell after this final irrigation. However, this yield reduction was still less than if one irrigation had been skipped during flowering.

In the same experiment there was little impact on fibre quality as a result of stretching irrigations after cut-out. Where there was no irrigation and no rainfall after cut-out, fibre length decreased by 0.02", strength decreased by 1.2 g/tex and micronaire increased by 0.28. Table 3.2.5 shows the effect of no irrigation and only 1 irrigation after cut-out on fibre quality, compared to a fully irrigated crop.

Table 3.2.5. Effect water stress after cut out on fibre quality. Comparison with fully irrigated*

	2006 (Sicot 71BR) No irrigation or rainfall after cut out	**2007 (Sicot 71BR)** 1 irrigation after cut out + no rainfall	**2008 (Sicot 70BRF)** 1 irrigation after cut out + no rainfall
Length difference (inch)	-0.02	-0.03	+0.07
Length difference (inch)	-1.3	-1.4	+0.06
Length difference (inch)	356 mm	+0.17	+0.17

* Data for handpicked areas where plastic sheet prevented rainfall on dry treatments. These experiments were conducted at Narrabri.

Innovative concepts in irrigation scheduling of cotton

Regulated Deficit Irrigation

Cotton can maintain boll growth for longer periods than vegetative growth when under mild water stress. Maintaining the soil moisture of cotton at a mild soil water deficit has been suggested as beneficial as it limits the potential for excessive vegetative growth while still providing adequate water for transpiration. Maintaining a small soil water deficit also maximises the opportunity to capture rainfall and minimises the occurrence of water logging.

It is difficult to maintain a constant mild soil moisture deficit using furrow irrigation; however some growers of Bollgard II cotton have adopted an approach where they irrigate Bollgard II crops at smaller deficits with faster irrigation run times. The aim is to reduce the potential for waterlogging by not completely refilling the soil moisture profile at each irrigation. Soil infiltration characteristics will influence the success of such techniques and will need highly skilled irrigation management.

Regulated deficit irrigation (RDI) has been investigated using centre pivot and lateral move (CPLM) and drip irrigation systems. These irrigation systems enable a higher level of control of irrigation volume, timing and placement. Simon White (2007) found that maintaining a regulated deficit of 79% of predicted evapotranspiration (ET) produced a 31.5% improvement in gross production water use index (GPWUI) compared to applying 100% of predicted ET (normal practice with high system capacity CPLMs). Similarly, Yeates et al. (2007) using drip irrigation found the highest yields occurred using 75 to 83% of predicted pan evaporation during flowering compared with 100% of evaporation. The higher water rate produced rank growth and lodging. The largest benefits from maintaining a regulated deficit was associated with crop management (preventing excessive vegetative growth, increased fruit retention and earlier crop maturity) and the increased ability for capturing rainfall.

Dynamic Deficits

Current irrigation strategies for cotton rely strongly on irrigation scheduling based on soil moisture content using fixed deficits for the majority of the season. Research by Steve Yeates, James Neilsen and Rose Brodrick has suggested there is an opportunity to refine irrigation scheduling by dynamically changing the soil water deficits to improve growth by avoiding plant stress during periods of high evaporative demand (lower deficits) and improve water use efficiency by reducing the need for irrigation during periods of low evaporative demand (larger deficits). Measurements of plant stress using leaf water potential showed that the plant stress response to soil water availability changed in response to differences in evapotranspiration (ET_0).

Brodrick et al. (2012) found that there may be considerable utility in delaying irrigation timing and extending opportunities to capture rainfall when ET_0 is low. This allows for more flexibility in cotton systems that require a significant number of fields to be irrigated at a point in time, and potential irrigation water savings. There was no difference in lint yield compared with a fixed deficit approach where irrigation timing was either earlier in response to forecasted high ET_0 or delayed when the forecast was for low ET_0. However, delaying the irrigation in response to forecasted low ET_0 enabled more rainfall to be captured than the other irrigation treatments leading to 0.8 ML/ha saving in irrigation water. These results indicate there is flexibility in irrigating cotton in response to future forecasts potentially saving water. However this study has highlighted the need for a definitive measure of plant stress to assist irrigation decisions to match plant requirements. Research is continuing to develop a framework to provide a method to identify plant stress (based on a continuous measure) which, coupled with current and future soil water deficits and with short term ET_0 forecasts, would allow the dynamic deficit approach to be used confidently and accommodate local conditions.

BIOTIC

BIOTIC is an irrigation scheduling tool developed in the U.S.A, based on canopy temperature using a temperature-time humidity threshold system (Upchurch et al., 1996). This system utilises wireless infrared thermometers (IRTs) that continuously measure canopy temperature. The existing thermal optimum approach to irrigation scheduling, BIOTIC, is limited in that it is designed for precision, low volume irrigation application systems. Therefore in its original form, BIOTIC has not been implemented in large soil moisture deficit systems, such as furrow irrigation. Recent research by Conaty (2010) in Australia has identified that this system could be adapted to suit deficit irrigation systems and is a subject of current research. WATERPak Chapter 2.4 contains additional details.

Overhead or Drip Irrigation Systems

Centre pivot, lateral move (CPLM) and drip irrigation systems offer a number of advantages and challenges for irrigation scheduling. For example, germination can be easily accomplished using sprinklers on a CPLM system, avoiding the need for water intensive pre-irrigation. Similarly, smaller, more frequent irrigation applications can be applied by CPLM and drip irrigation systems, offering the flexibility to maintain the soil moisture deficit at a point which maximises rainfall capture and prevents waterlogging, moisture stress and rank growth (see RDI above).

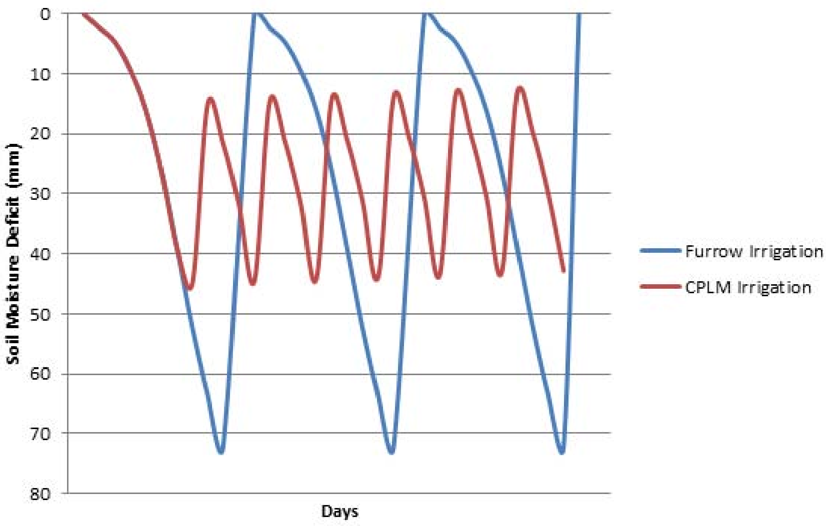
However, in contrast to furrow irrigation systems, CPLM and drip systems do not have the ability to apply large volumes of water to 'catch up' if the crop experiences a period of high water use. Such a scenario is best avoided by managing the soil moisture reserve and purchasing an irrigation system with sufficient system capacity .

The soil moisture reserve can be managed by building soil moisture levels over the early life of the crop, when water use is low. It is also important to monitor weather forecasts and ensure that the soil contains sufficient moisture prior to predicted high water use periods. System capacity should be high enough to satisfy peak crop water demand but not so excessive that capital and running costs are too high. The calculation of system capacity is covered in detail in WATERpak Chapter 5.6.

Centre pivot and lateral move systems usually apply much smaller amounts (for example, 30 mm) than furrow systems. Furthermore, skilled operators will not necessarily refill the profile with every irrigation. For example in Figure 3.2.5, furrow irrigation is triggered at a soil moisture deficit of about 70 mm and irrigation completely refills the profile. In contrast, CPLM irrigation is triggered at a deficit of around 45 mm and 30 mm of irrigation is applied to take the soil moisture deficit to around 15 mm. It would be possible to modify the application strategy and timing throughout the season in response to different plant growth stages or anticipated weather conditions.

Drip irrigation systems may be operated in a similar manner or may be operated even more frequently (e.g. daily) with smaller applications.

Figure 3.2.5. Hypothetical example of the possible difference in soil moisture arising from different furrow irrigation and CPLM scheduling approaches.

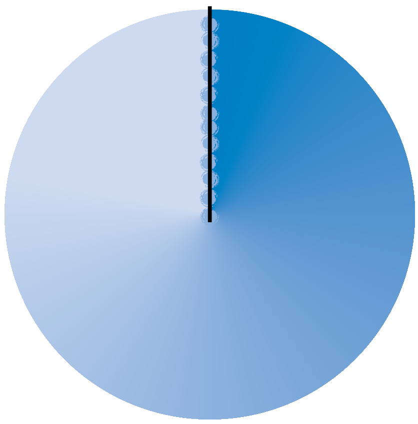


Timing and volume of irrigation water to be applied is best predicted by calculating the water used by the crop. This is done by calculating the evapotranspiration (ET) of the crop using a calibrated crop factor and reference evapotranspiration (ET_0). See WATERPak Chapter 2.1 for more details on calculating daily crop water use using these methods. Tools such as WaterSched2 may also be useful to assist with ET based scheduling. Deficit irrigation (less than 100% ET_c replacement) is often practiced in limited water situations but should be undertaken with care, particularly during flowering and peak evaporative demand.

In addition to scheduling drip irrigated and overhead irrigation systems using evapotranspiration data, it is also important to monitor both the crop and the soil water content. Monitoring your crop to ensure that it is not under stress is as important in these systems as for furrow irrigation systems.

One final important concept for scheduling with CPLM systems is to understand that the soil moisture deficit is not uniform across the field. Consider a centre pivot machine that is applying 30 mm of water to a 50 mm soil moisture deficit. The soil immediately in front of the machine (about to be irrigated) would have a 50mm deficit whilst the soil immediately behind the machine (just irrigated) would have a 20 mm deficit (Figure 3.2.6). Assuming uniform daily water use, a point on the opposite side of the circle would be half way between these extremes, with a deficit of 35 mm. Such considerations can become complicated, particularly for new users and particularly after rainfall events. The OVERSched tool was developed to help visualise these soil moisture gradients so that irrigation management can be improved.

Figure 3.2.6. Visualisation of potential soil moisture gradient in a centre pivot field. One side of the machine has dry soil whilst the other side has moist soil.



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3.3 Managing irrigation of cotton with limited water

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Key points

- Decide on a strategy preseason, before planting; be flexible as things may change for better or worse during the growing of the crop.
- Know what water is available from all sources; do not discount stored soil moisture and predicted rainfall. Calculate the area you are able to irrigate with the available supply.
- Select fields on the basis of efficient water supply and good yield history and plant water holding capacity.
- Choose a variety normally suited to your production region. Best performing dryland varieties in your region should be a guide.
- Characteristics in a variety should be high yield potential, inherently good fibre quality parameters, even in tough conditions, and indeterminacy of growth habit.
- Avoid excessive nitrogen which encourages rank vegetative growth and wastes irrigation water.
- The irrigation strategy in limited water scenarios is to limit or minimise the amount of stress on the crop. It should be based on water available and cropping system. Concentrate available water into the flowering period.
- Approach defoliation as normal, deciding on the last harvestable boll and follow maturity up the plant to determine the defoliation date.

In a limited water situation, the normal range of factors needs to be considered but there may be a shift of emphasis. In particular, the management aim moves from bales/ha to bales/ML. A number of agronomic decisions will need to be made at, or prior to, sowing as part of the planning associated with land preparation and sowing. These decisions include row configuration, nitrogen application method and amount, sowing date and varietal selection. The critical requirement is to ensure that agronomic management does not result in an excessively vigourous crop nor delay crop maturity too much.

How much cotton should I plant and irrigate?

When water becomes the limiting resource for production, the relative importance of various management decisions begins to change. Two key questions arise:

- What area of land should be prepared for irrigated cotton?
- How should the remaining area be prepared to allow for flexibility if conditions improve closer to planting?

The answers are a function of the total water supply available for the crop from all sources: from the river and bore allocation, on farm storage and any expected off allocation pumping. No single option is the best in every season, but research has indicated which options perform best over the long term, when taking into account year-to year variation in weather.

Growers in situations of limited water supply should consider what area to plant and how much of this should be irrigated. The answers to these questions will be influenced by many factors specific to the location, farm and grower.

A number of studies have been undertaken to consider the area to dedicate to irrigated production. The results are summarised in Table 3.3.1. Generally the answer is to aim to irrigate an area that will allow 5 to 6 ML of supply per ha.

To allow an appreciation of the risk level involved, data has been presented on the supply required to ensure that the break-even yield is attained in 9 years out of 10. In most cases, the supply which maximises the average returns is greater, and so based on the long-term weather record, the risk of failing to break-even using this supply is less than 1 in 10.

Note that these figures refer to the available supply, not the expected application, and are calculated based on a whole farm irrigation efficiency of 75% (That is, ¾ of the water supplied is used by the crop as evapotranspiration. This accounts for storage, distribution and application losses). If your irrigation efficiency is markedly less than this, the figures will need to be adjusted accordingly.

Table 3.3.1. Water supply required on September 1 to reduce the risk of failing to break even to less than one in ten and the supply which maximises returns per megalitre (N.B. Solid plant cotton; assumes a whole farm irrigation efficiency of 75%).

Region	Supply to break-even in 9 years out of 10 (ML/ha)	Supply to maximise returns per megalitre (ML/ha)
Emerald	4.5	5
Darling Downs	5.0	5
St George	5.5	5
Border Rivers	5.2	6
Gwydir Valley	5.3	6
Namoi Valley	5.2	6
Macquarie Valley	6.3	6

This question can be re-examined just prior to the first irrigation. At this time, the supply that needs to be on hand is less, as the water to establish the crop has already been dealt with. The long-term weather record suggests an irrigation supply of 3 to 4 ML per ha will maximise returns at this point. The results for the various regions are given in Table 3.3.2. and the supply for breaking even is again presented.

Adjusting to lower water availability by removing selected rows after establishment (converting to skip row) is detrimental to the overall performance of the field. Row configuration decisions (see below) should be made pre planting. Planting with the option to remove rows later is not desirable for two reasons.

1. Water used by the plants in the skip row has been wasted on unproductive growth.

2. Plants remaining have suffered more moisture stress than would have otherwise been the case, and therefore have difficulty in recovering from this stress for the entire season. Early stress leads to slow growth and fruit development and premature cutout.

Table 3.3.2. Water supply required on December 1 to reduce the risk of failing to break even to less than one in ten and the irrigation supply which maximises returns per megalitre (N.B. Solid plant cotton; assumes a whole farm irrigation efficiency of 75%).

Region	Supply to break-even in 9 years out of 10 (ML/ha)	Supply to maximise returns per megalitre (ML/ha)
Emerald	2.3	3
Darling Downs	3.2	3
St George	3.5	3
Border Rivers	3.2	4
Gwydir Valley	3.4	4
Namoi Valley	3.2	4
Macquarie Valley	4.0	4

In light of this, sowing more cotton than the estimated water supply would suggest allows reassessment prior to the first in-crop irrigation. If this favourable rainfall does not occur, some area can be reverted to dryland production. The question of what total area to sow to cotton is independent of the question of how much to irrigate: dryland cotton is a legitimate cropping option for the remaining, non-irrigated area. This depends on your location. The decision of how much dryland cotton to sow should be based simply on those factors which dictate whether dryland cotton production is viable. Key variables here are the amount of stored soil moisture and the anticipated rainfall, hence the yield expectation.

Row configuration

If, when calculating the area to plant, the irrigation supply is pushed below 5-6ML per ha, then partially irrigated skip row may become an option in some regions. Irrigated skip row systems have been suggested as offering some potential for increasing water use efficiency in water limited situations. Skip row cotton is being considered for use in limited water situations more widely for a number of reasons. The practice:

- Extends the planted area to allow utilisation of full moisture profiles.
- Buys some time in which to benefit from in-crop rainfall.
- Minimises the potential for fibre quality discounts.
- Allows easier insect and weed management with biotechnology.
- Takes advantage of marketing options and upside from growing cotton.
- Offers significant variable cost savings.

Skip row configurations function by increasing the volume of soil that plants have to explore, providing a bigger reservoir of available moisture and allowing the plants to hold on for longer during dry periods. Skip row cotton provides an 'in between' option for increasing the area of cotton which can be grown, allowing some upside in production if conditions improve and far less downside in potential fibre quality discounts if the season deteriorates.

However, in some cases, inherent growing characteristics such as soil type, in-season rainfall, and location may mean there is minimal advantage in adopting skip row practices.

Research trials have established that row spacing has a larger effect on yield and quality than number of plants per metre of row. Evidence from rain-fed cotton trials shows there is little or no yield reduction between 4 and 12 plants per metre.

There are a range of different configurations being used by growers across the cotton industry in semi-irrigated situations. These include:

- single skip (two plant rows, one skipped row);
- 60 inch (1.5m) rows;
- 80 inch (2m) rows (or 1 in 1 out);
- double skip (two plant rows, two skipped rows); and,
- super single (one plant row, two skipped rows).

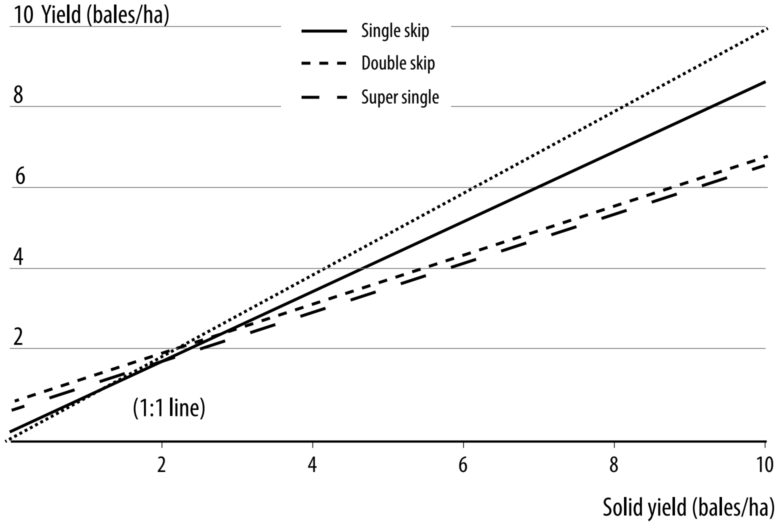
The positive and negative features of each configuration, including the relative water use efficiencies, depend on the individual situation. What works best in one farming system may not in another due to differences in soil type, environment, cropping history, available equipment, water availability and other factors.

Growers contemplating whether they would benefit from using skip row configurations, and which skip row configuration they should use, should consider the yield, cost and fibre quality mix of each configuration. Extensive research has shown that while skip row cotton does limit yield potential (Figure 3.3.1.), the combination of reduced fibre length discounts and variable cost savings in growing skip row cotton often lead to a better risk/return proposition. Growers need to consider their yield potential, based on all the factors discussed later in this chapter.

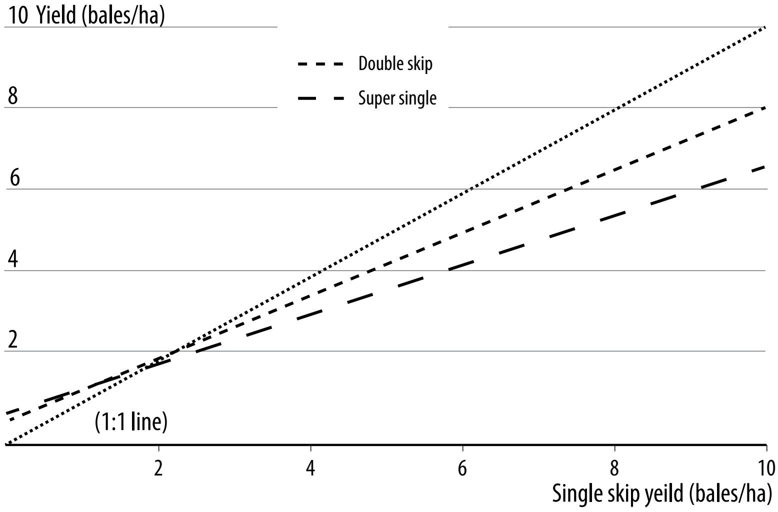
Figure 3.3.1 - Comparison of average solid and skip row yields in dryland and irrigated

systems across several seasons and regions (Bange, 2012).

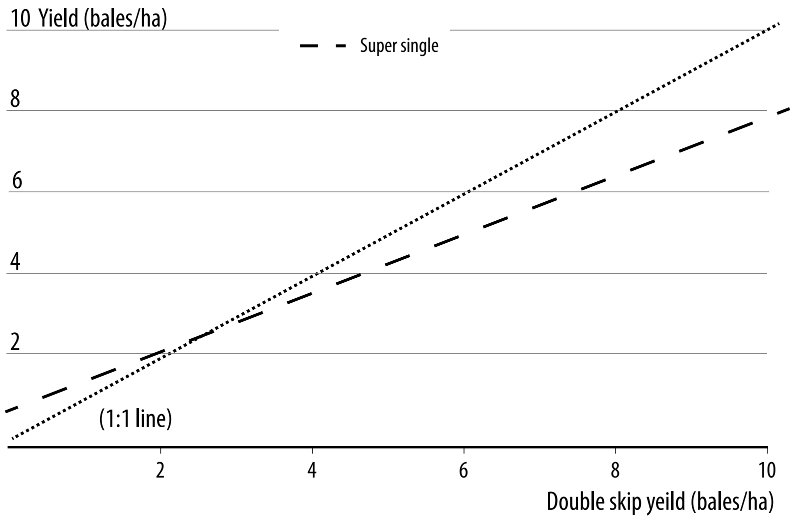
Single Skip has the highest upside yield potential of these configurations,



Crossover for single 2.1 (solid) for double 2.2 (solid) for super single 2.5 (solid)



Crossover 2.3 bales (single) Crossover 2.6 bales (single)



Crossover 2.3 bales (double)

however it will also use its moisture profile the quickest. Having a plant row 50 cm one side and a one metre skip row to the other, this configuration is best suited to situations on heavier soil types with high plant available water content (PAWC) and more irrigation water and rainfall availability

Double Skip having a plant row 50cm one side and a 1.5m skip row to the other, this configuration tends to impose small amounts of moisture stress to the plant, restricting early excessive vegetative growth compared with wider configurations. Plants can be prone to lodging, especially vegetative branches, which take advantage of the extra light available in the skip area. It is best suited to drier profiles and hotter environments when compared to single skip environments.

While **one-in-one-out (alternate row or 80 inch)** cotton has not been included in the research illustrated in Figure 1, grower experience and some preliminary trial work has shown its yield potential to be slightly higher than double skip in certain circumstances. Preliminary trial results suggests that despite increased water use in the alternate row configuration compared with double skip, this did not result in increased stress later in the season as yield was unaffected. The equidistant row spacing in the alternate row configuration may contribute to better access to soil moisture and investigations are continuing to determine the potential of these configurations. A more uniform growth habit in 80 inch cotton can reduce lodging and allow better spray penetration and defoliation processes when compared to double skip.

A couple of advantages perceived by some double skip growers compared to 80 inch are:

- Growth management is easier as vegetative growth seems to be reduced.
- Double skip is easier to cultivate, especially compared with 80 inch systems where the row is in the middle of a 2m bed.
- It is more difficult for water to sub to the centre of the bed when watering up 80 inch rows.

Super Single (one-in-two-out) has been tried in semi-irrigated situations. The widely spaced plant rows (3 metres apart) means the yield potential and potential upside in a good season is severely limited. However, it may be an option with a full soil moisture profile at planting and minimal irrigation water resources. This configuration allows growers to minimise growing costs as well as limit the likelihood of fibre quality discounts.

Skip Row Irrigation Strategies

Irrigation strategies used in skip row cotton need to work on the principles that yield is maximised by avoiding or at least minimising moisture stress while the plant is flowering (Table 3.3.4.).

With this in mind, the optimum timing to maximise the benefit of each irrigation will depend on the field, the amount of water available and the environmental conditions your crop is enduring. This is why it is so important that a range of monitoring techniques is used.

Table 3.3.4. Yield loss (%) per day of water stress (extraction of > 60% plant available water) (Source Yeates et al. 2010#; Hearn and Constable 1984*)

	Past Conventional*	Bollgard#
Squaring	0.8	1.1
Peak flowering	1.6	1.7
Late flowering	1.4	2.7
Boll maturation	0.3	0.69^

^ 14 d post cut out

Furrow irrigation of skip cotton

Irrigation of skip cotton may require a different approach, particularly when using furrow irrigation. Water extraction from the soil profile is often far less uniform than under a solid plant configuration, with the soil between the plant rows being drier than that in the skip, particularly in double skip. Furrow irrigation between the plant rows will be slowed considerably by the larger soil moisture deficit in the dry soil. Conversely, irrigation in the skip, particularly in double skip, may be faster as the deficit is smaller, but lateral movement of soil moisture to the plant rows may not be ideal. Three options might be considered:

1. Irrigate between the plant rows only. In this situation a higher efficiency may be more likely if flow rates are increased to overcome the effects of the large soil moisture deficit. High flow rates should be managed closely as tailwater volumes can be significant, especially if irrigation is allowed to continue after the water has come through.
2. Irrigate the skip rows only. In this situation, the effective lateral movement of water must be monitored carefully. Running this form of irrigation for a long period to ensure adequate wetting of plant rows is likely to result in excess tailwater and water losses deep in the profile beneath the skip rows. If plant rows remain reasonably dry following irrigation, plants will only be able to access water in the skip, where there may be less roots and access might be more difficult for the plant.
3. Irrigate plant and skip rows. In this situation, a more even wetting front might be achievable, although it may still be necessary to have a higher flow rate in plant rows. This strategy is most likely to result in a wet field with reduced potential for rainfall capture until water has been used by the crop.

Increased monitoring of irrigation performance will be extremely useful for determining the most appropriate strategy for individual circumstances. Moisture probes in skip and plant rows can provide valuable information and furrow irrigation performance evaluation (see Chapter 5.3) can be used to determine the efficiency of different options. Breakouts will be more likely under scenarios (1) and (2), particularly where flow rates need to be very high to ensure efficiency. To avoid breakouts across soft rows, wheel tracks may need to be worked out.

The first irrigation

The timing of the first irrigation in skip row cotton is critical. Stretching it too far can result in rapid-cut out, resulting in a restricted boll load and triggering crop re-growth when moisture eventually becomes available. This will result in a big maturity gap making the crop difficult to finish and defoliate. The decision of when to start irrigating also needs to consider the capacity to water all areas to avoid being late on the last fields. Although irrigation intervals may be greater in skip row, each irrigation may use as much if not more water than solid plant.

Field choice

Fields with a history of high yield may be valuable, but reference to water use records may show that yield is commensurate with water use. In this case, yield history alone would be of limited advantage. Rather it is necessary to consider either water use efficiency or yield under restricted water supply.

If only part of the irrigable area can be planted with the available water supply, the choice of which fields to sow and irrigate will be governed by yield expectation and efficiency of water supply. On most properties, there are far greater gains to be made in storage, distribution and application efficiency than in crop water use efficiency.

Soil type and moisture status are critical elements when determining the priority of fields to plant. Target fields with high plant available water holding capacity; a bigger bucket of water will be beneficial, especially for buffering against stress in hot temperatures, between irrigation events and as the crop dries down the soil profile late in its development. Also calculate how full soil profiles are, ideally with the aim of establishing the crop on rain moisture. Using irrigation water to establish the crop is appropriate only if there is no other option.

The efficiency with which water is supplied to the field is more variable than the efficiency with which a crop uses the water delivered to it. Thus proximity to the best storages and/or being supplied by the best channels are factors to consider in field choice.

In most circumstances, fields with drip or centre pivot/lateral move (CPLM) systems should be cropped as a priority as these systems can apply small amounts of water as required throughout the season. In addition, CPLM systems have a distinct advantage over both drip and surface irrigation in their ability to germinate crops. Alternative row spacing strategies are not often utilised under these irrigation systems as small, regular water applications can keep solid plant cotton growing through the season with greater potential upside when rainfall occurs.

Nitrogen fertiliser

As discussed in WaterPAK Chapter 3.1 and NUTRIpak, nitrogen fertiliser application should be made on the basis of soil tests, petiole tests or at least cropping history. This is given added significance in the water limited situation. Crops which are water limited are less responsive to applied nitrogen and so excess nitrogen, at best, is non-productive. Further, if excessive water supply from irrigation or rainfall occurs in combination with high nitrogen, it may lead to the development of a large canopy, resulting in increased water requirements that cannot be met. It may also lead to a delayed maturity resulting in a need for continued water supply.

In scenarios where excessive nitrogen is present, the use of growth regulators at cut out should be considered to limit the detrimental effects. Using high rates of growth regulators at this period of crop growth will restrict vegetative growth, promote crop uniformity and redirect efforts into filling and maturing set bolls.

Variety choice

Choice of variety should be based on matching the variety to your production region. This is particularly so with respect to disease and season length.

The CSIRO and Cotton Seed Distributors conduct many trials across all growing regions which examine the performance of varieties in all growing scenarios. Many studies in Australia have shown that the varieties which do best under irrigated conditions are generally those which do best under dryland or reduced irrigation conditions also.

The principles behind selecting a variety for limited water scenarios are similar to those in selecting a dryland variety. Firstly look for varieties with high yield potential for your region and that have an inherently good fibre quality characteristic, especially fibre length. Varieties with inherently long fibre provide a buffer against reductions in fibre length which may occur due to water stress.

Varieties should be indeterminate in nature to respond to late season rainfall or irrigation if forthcoming. The advantage of early maturing or determinate varieties under dryland production which is seen in some overseas production areas does not apply in Australia. The advantage of short season varieties in these situations is based on the need to avoid a terminal drought. Using such varieties in Australian growing areas imposes an absolute yield limitation from the time of sowing. There is thus no scope to take advantage of any changes in water supply or rainfall that may occur during the season. Such varieties also tend to shut down abruptly when any stress is encountered and once they have ceased fruit production, do not readily recommence. Clearly this is a particular risk where water is limited.

If sowing is significantly delayed in the hope of receiving planting rain or further soil recharge, a shorter season variety than usual or a lessening in the row configuration may also need to be considered. Variety selection guides are generally released annually by seed providers (for example see www.csd.net.au).

Sowing date

The optimum date of sowing differs between a fully irrigated crop and crops grown with a restricted allocation. Cotton yield declines with delayed sowing due to the shorter time available to initiate and mature an adequate number of bolls.

As a general rule, as the available water supply decreases, the expected decline in yield potential with sowing date begins somewhat later. This is because the crop is already yield-limited and so doesn't need as much season length to achieve the new water-limited yield potential.

This is illustrated in Table 3.3.5. using simulation output from the OZCOT model. It should be noted that in this example, some of the supply levels are below that which might be expected to provide break-even returns anyway. While there is more flexibility in sowing date with lower allocation, excessive delay must be avoided. This may increase the risk of quality downgrades due to the chance of maturing late bolls in cool weather.

In northern areas where there is a longer growing season and more summer rainfall, low allocations may show an optimum sowing time rather than a simple decline. This is because (1) the impact of late sowing is less in these areas and (2) there is potential to match crop water demands to the long term rainfall distribution.

Table 3.3.5. Sowing date after which yield declines for different irrigation supplies

Region	Irrigation supply per hectare		
	2 ML	4 ML	6 ML
Emerald	30 Nov	30 Nov	30 Nov
Darling Downs	15 Nov	30 Oct	30 Oct
St George	30 Nov	15 Nov	15 Nov
Border Rivers	30 Nov	15 Nov	30 Oct
Gwydir Valley	15 Nov	15 Nov	15 Oct
Namoi Valley	15 Nov	30 Oct	15 Oct
Macquarie Valley	15 Nov	30 Oct	30 Sep

Irrigation scheduling with limited water

By and large, the general practice when irrigating with limited water is to adhere to the optimised irrigation strategy for your region using the suggested level of supply. This will mean a reduction in the irrigated crop area. A generalised approach is outlined in WATERpak Chapter 3.1.

Establishing on rain moisture is preferable. However, if that is not an option then watering-up is preferred to pre-irrigation, as less water is lost from the system in establishing the crop. After pre-irrigation, the soil profile must be allowed to dry down to allow for trafficking by tractors and other implements, and this water is a loss from the system. Watering up allows for the seed to be placed much more shallowly and the crop can establish much more quickly. However, the general management difficulties associated with watering-up need to be borne in mind.

Don't risk stretching the irrigation interval beyond the target deficit. While this may pay off in some seasons, it is better to skip the last irrigation to allow maximum chance of catching rainfall or increased allocation before locking in to a reduced yield potential.

With very severe shortages there may be some advantage in delaying first irrigation a little. This is preferable to risking stressing the crop during flowering, when the crop is more sensitive (see Table 3.3.4. and WATERpak Chapters 2.1 and 3.1)

Some Irrigation Scenarios

The following scenarios are based on grower experience and their success in individual situations and will be influenced by environmental conditions, including in-crop rainfall and the chosen row configuration.

- **One irrigation available.** Delay irrigating for long as possible into flowering without letting the crop go into serious stress or fully cut out. This may be at 4 to 5 nodes above white flower (NAWF). This will limit yield potential should further irrigation water become available later on but will give the best opportunity for good fibre quality on the fruit that is set. If planting rainfall is not forthcoming, this one irrigation at planting will establish the crop, and the crop can be managed as if it was dryland from this point onwards.
- **Two irrigations available.** Target the first irrigation early in the flowering period and the second at around cut-out to provide adequate moisture to mature the set fruit. Close plant monitoring around this second irrigation is essential as growth regulator may be required to prevent re-growth and target resources into filling bolls.
- **Three irrigations available.** Use a similar approach to two irrigations, although the extra irrigation can be applied following the first irrigation, with the aim to extend the flowering period and prevent early cut-out. The third irrigation can then be applied at cut-out. The aim of the third irrigation is to help add size to later bolls.

In any of these scenarios, if the crop is looking good enough, a decision to purchase more water can be made.

Soil Moisture monitoring

As with fully irrigated crops, soil moisture monitoring is invaluable for irrigation management in limited water situations. As is normally the case, probes should be located in the predominant soil type of the field. Some guidance is provided in WATERpak Chapter 2.7.

In addition, it is advantageous to have moisture probes positioned in both the skip row as well as the plant line. This will give an accurate measure of crop water extraction when the plant is growing well and help predict when skip row moisture will run out. Probes can be double checked with a spade or moisture spear to determine whether roots are getting across into skip rows. Finally, calibrated probes can deliver actual daily water use, which is invaluable for determining correct irrigation date.

Plant Monitoring

Plant monitoring is essential to track the progress of the crop throughout the season. In limited water situations, timing of irrigations should take into account both the soil water and plant stress. Plant vigour can be measured using squaring nodes (before flowering), Nodes Above White Flower (NAWF) (during flowering) and Vegetative Growth Rate and fruit numbers throughout the season. This information can be benchmarked against 'ideal' crop growth using the Cotton CRC Crop Development Tool.

Case Studies

A number of trials have been undertaken to evaluate the impact of different watering treatments on yield and fibre quality and the water use efficiency of skip row treatments. As can be seen below, the results from these trials are not always consistent, highlighting the variability in growing cotton in this way. Results are particularly reliant on the volume and timing of in crop rainfall.

Row configuration case study: Irrigation trial – "Redbank" Gwydir Valley, 2010/11.

This trial compared three row configurations (solid, single and double skip) with 3 watering regimes superimposed (Full - 8 irrigations; Semi- 3 irrigations; Limited - 1 irrigation).

The trial was established on rain moisture and all treatments apart from the fully irrigated solid plant had irrigation scheduling determined by moisture probes and nodes above white flower (NAWF). The semi-irrigated regime had three irrigations timed at 7, 5-6 and 4 NAWF whilst the limited irrigation regime had one irrigation timed at 4 NAWF. Evapotranspiration was calculated using percentage ground cover to determine appropriate crop coefficients (see WATERpak Chapter 2.1) although this method does not account well for the level of stress that limited water crops may be experiencing.

Table 3.3.6. Yield and Water Use in Redbank, Limited Water Experiment 2010-11

Irrigation regime	Full	Semi	Limited	Semi	Limited	Semi	Limited
Row configuration	**Solid**	**Solid**	**Solid**	**Single**	**Single**	**Double**	**Double**
Yield (b/ha)	12.54	7.08	6.67	8.65	6.26	6.81	5.09
No. Irrigations	8	3	1	3	1	3	1
Irrigation Applied (ML/ha)	4.15	3.20	1.43	2.64	1.11	2.28	0.89
Effective Rainfall (ML/ha)	2.28	1.87	1.94	1.61	1.69	1.53	1.60
Starting Soil Water (ML/ha)	2.20	2.20	2.20	2.20	2.20	2.20	2.20
Ending Soil Water (ML/ha)	1.15	0.56	0.00	0.57	0.11	0.61	0.11
Total Water (ML/ha)	7.48	6.71	5.57	5.88	4.89	5.39	4.58
Estimated Evapotranspiration (mm)	735	687	582	732	639	752	679
IWUI (Bales/ML)	3.02	2.21	4.66	3.28	5.65	2.99	5.72
GPWUI (bales/ML)	1.68	1.06	1.2	1.47	1.28	1.26	1.11

By the end of December the skip row treatments had started to extract water from both the plant line and the skip, effectively giving the skip-row treatments access to more water than the solid treatments from that point on. By the end of the season, the semi and fully irrigated solid treatments were extracting moisture down to 100 cm, the limited solid treatment down to 120 cm, the single and double-skip semi irrigated treatments were extracting to 120 cm in the plant line and 100 cm in the skip. The single and double-skip limited irrigation treatments were extracting water from 120 cm in both the plant line and the skip by the end of the season.

Accounting for the skip proved to be a challenge in calculating plant available soil water. Water use is difficult to calculate in real time in skip row systems and requires the development of new tools or technologies to accurately determine water use and root exploration.

Estimating crop evapotranspiration (ET_C) using a calibrated crop coefficient based on canopy cover worked very well in the solid, fully irrigated and the semi-irrigated treatments, but this approach over-estimated water use in the limited irrigations and skip row treatments because it does not account for declines in crop water use due to plant stress and tended to overestimate the amount of water in the skip-rows.

Yields were highest in the solid, fully irrigated treatment, followed by the single-skip, semi irrigated treatment and the solid, semi irrigated treatment (Table 3.3.6.). However, water use was higher in the fully irrigated and semi irrigated solid plant treatments than in the single-skip semi-irrigated treatment.

Yield was much lower in the double skip scenarios, with the semi-irrigated double skip configuration yielding similarly to the limited solid plant configuration, even though more irrigation water was applied.

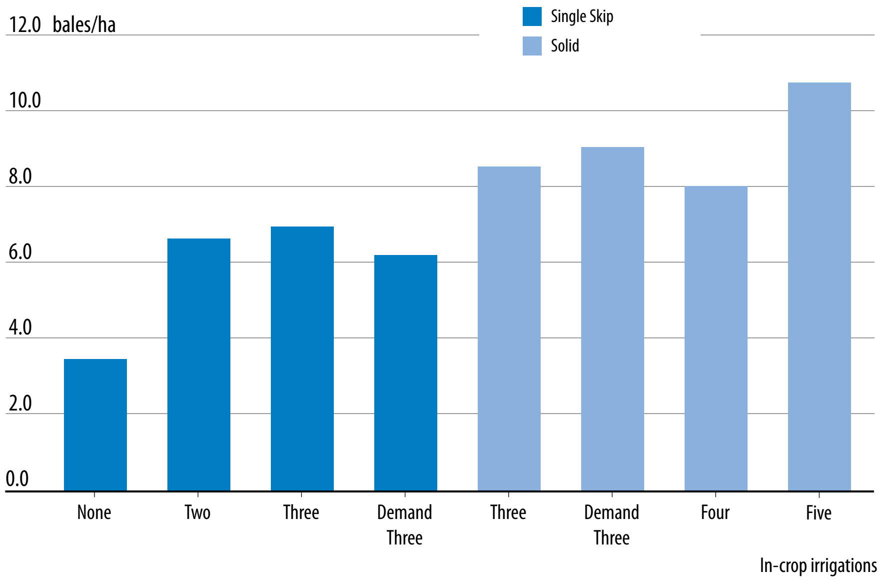
The results of this particular trial suggest that the single-skip semi irrigated treatment provided reasonable yields with high water use efficiency, suggesting that it may have potential in a limited water situation. The efficiency gain in the single-skip irrigated treatment indicates that it may have potential in a limited water situation, but more research is needed to develop irrigation strategies for limited water situations, across a range of environments to understand the consequences of the timing and amount of irrigation applied on plant stress, yield and quality.

Row configuration case study: Irrigation trial - Auscott Namoi Valley, 2002/03.

In this trial, a combination of eight different irrigation and row configuration treatments were tested. All treatments received a pre-irrigation and a flushing but then received none, 2, 3, 4 or 5 in-crop irrigations with two additional 'on-demand' treatments. Four of the eight treatments were grown in a 2:1 pattern or single skip row configuration.

The yields achieved ranged from 3.4 to 10.5 bales/ha with higher yields achieved with more irrigations and water applied. The exceptions were the skip on demand with 3 irrigations and solid plant with 4 irrigations, which were waterlogged during a rain event following the first crop irrigation. Subsequently the solid plant treatments achieved higher Irrigation Water Use Indices (bales/ ML applied) than the skip plant treatments, which improved with higher numbers of irrigation events.

Figure 3.3.2. Single skip and solid plant yield under a range of irrigation scenarios



The skip irrigation treatments followed a negative IWUI trend with increased application volumes. In other words, the yield gains were not big enough to increase the IWUI. The trial results from this year lead to the conclusion that the cotton area in a year with limited water supply should be limited to allow for a full irrigation program.

Limited water case study: Defoliation under drought conditions, Darling Farms, 2002-03

On Darling Farms, between 3 and 6 irrigations were applied to upland cotton, with the majority of the farm receiving 4. Fields had their last irrigation applied as early as the 9th January and as late as the 14 February, where traditionally this is applied in the last week of February. The management approach taken was to irrigate as required, rather than stretching the 1st irrigation. Most plants remained relatively green and retained most of the fruit provided they had 3 or more irrigation's. Based on advice from dryland cotton consultants and early trial work at Dirranbandi, defoliation was approached as normal.

Maturity was determined by the cut boll method on the last harvestable boll. Many of the very top fruit were spongy and would crack open if pressed long before the seed was mature. As a result, defoliation dates were only slightly earlier than if the crop had received full water. Given that some crops were dried down (last irrigation to defoliation) for 45 –50 days, boll maturity was found to move up the plant at a slightly slower rate than normal. Generally 3 days per node is required, however under these circumstances 4 – 5 days per node was found.

The defoliation program was:

- **1st Application.** 80 – 100ml Dropp® liquid applied 3 days before the designated top boll was mature.
- **2nd Application.** 1 – 1.5L of Ethephon® applied either alone or with 20ml of Dropp® liquid if significant green leaf remained on the plant. The 2nd application occurred when enough leaf shed exposed bolls, generally 7 days later.

Opening the very top fruit on water stressed plants depends on the size of the discount on fibre quality versus extra yield obtained from picking this fruit. It was felt that in all cases it was worth chasing the extra yield and the chance of quality discounts.

Table 3.3.7. below shows the effect of each irrigation on fibre length and micronaire. The assumption has been made that limiting water would affect length and micronaire but not necessarily colour or leaf / trash content. A Dunavant P& D 2002 crop sheet was used to calculate discounts using a grade 31, leaf 1 for all calculations, with only length and micronaire varying. Although this is not the actual premium or discount we received it does highlight the effect of limiting water on fibre quality. Table 2 details the different response between varieties to fibre quality to limited water situations.

It was noted that limiting water appeared to affect only fibre length. The timing of moisture stress relative to the development of the boll load is important here, in addition to the canopy size and boll load. With reduced le-ngth comes a lower requirement for carbohydrate required to thicken the fibre. This limited dataset shows that some varieties, such as 189/289i and S80, produce less short fibre than other varieties given 3 or 4 irrigations. It highlights that the cotton plant is a remarkably robust plant and fruit continued to develop and mature relatively similar to normal even under extremely stressful conditions.

Acknowledgement: Thanks to Dr Phil Goyne, Mr Mitch Abbo, Mr Jason Fritch and Mr Stefan Henggeler for their contributions to this chapter.

Table 3.3.7. Comparison of multiple simulation results from Narrabri and Emerald

Multiple scenario comparison – end of season status
Farm: Big Bolls – Narrabri

Field: Field 1, Crop: 2003-04 plant

Variety: SICOT189, sown 01.10.03

Scenario	Run date	Final irrigation	Total irrigation	Pre-run pumped (ML)	Post-run pumped (ML)	Water pumped (ML)	Water left (ML)	Total rain (mm)	60% open	Total bolls (/m^2)	Yield (bales/ha)	Irrigation water use index (bales/ML/ha)
3 ML/ha	01.10.03	20.12.03	2	0.0	2.7	2.7	0.3	353	21.02.04	82	4.6	1.7
5 ML/ha	01.10.03	24.01.04	4	0.0	5.2	5.2	-0.2	375	03.03.04	106	7.2	1.38
7 ML/ha	01.10.03	29.01.04	4	0.0	2.8	5.8	1.2	388	12.03.04	119	8.9	1.53
3 scenarios					**4.5**	**4.5**	**0.4**			**102.3**	**6.90**	**1.54**

Multiple scenario comparison – end of season status
Farm: Emerald

Field: Field 21, Crop: 2003-04 crop

Variety: SIOKRAV16, sown 01.10.03

Scenario	Run date	Final irrigation	Total irrigation	Pre-run pumped (ML)	Post-run pumped (ML)	Water pumped (ML)	Water left (ML)	Total rain (mm)	60% open	Total bolls (/m^2)	Yield (bales/ha)	Irrigation water use index (bales/ML/ha)
3 ML/ha	01.10.03	19.12.03	2	0.0	3.0	3.0	0.0	303	30.01.04	82	5.70	1.90
5 ML/ha	01.10.03	06.01.04	3	0.0	4.8	4.8	0.2	322	06.02.04	94	7.20	1.50
7 ML/ha	01.10.03	06.01.04	3	0.0	4.8	4.8	2.2	324	18.02.04	97	7.50	1.56
3 scenarios					**4.2**	**4.2**	**0.8**			**91.0**	**6.80**	**1.65**

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Hearn A.B. and Constable, G.A. (1984) Cotton. In Goldsworthy, PR and Fisher, N.M (eds), The Physiology of tropical food crops. John Wiley and Sons Ltd. Pp 495 – 527.

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3.4 Impact of waterlogging on cotton

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Key points

- Waterlogged soils reduce the access of the roots to oxygen, impairing root growth and function and ultimately nutrient uptake. Toxic gases in the waterlogged soil can also increase.
- Waterlogging reduces cotton yields by causing fruit shedding and slowing growth of new fruiting sites which reduces the number of bolls on the plant.
- Waterlogging can be avoided by optimising field design, bed formation, and irrigation scheduling. The application of some foliar fertilisers may also assist in fields known to waterlog.

Cotton is known to be poorly adapted to waterlogged conditions. In Australia, cotton production is concentrated on soils with inherently low drainage rates, which, combined with the almost exclusive use of furrow irrigation and a summer dominant rainfall pattern, results in a significant risk of intermittent waterlogging.

Causes of waterlogging

When a soil is waterlogged the access of the roots to oxygen is impaired, reducing their ability to respire thus reducing root growth and function and ultimately nutrient uptake. There is also a build-up of toxic gases such as carbon dioxide and ethylene that are generated by the roots and micro-organisms which can impair root and whole plant function.

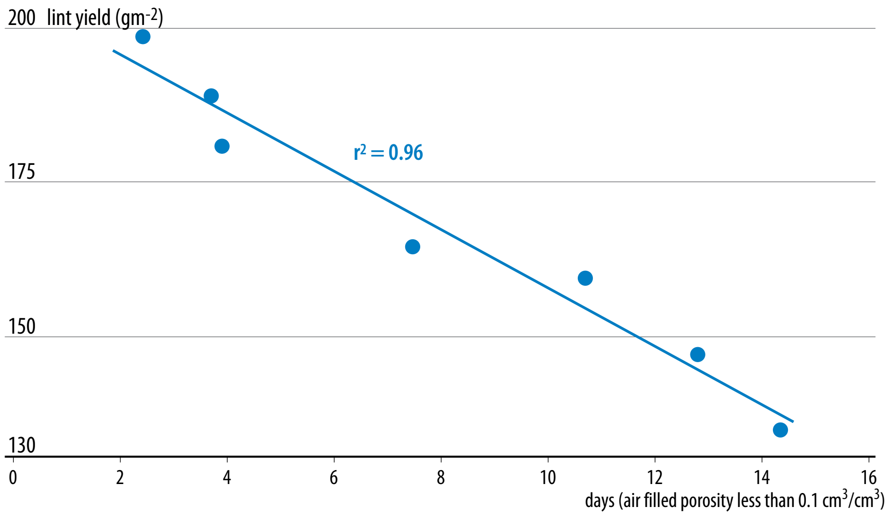
The waterlogging problem can be exacerbated through additional factors such as:

- soil compaction. There is less space for air to be present in the soil and transfer of air is impeded.
- excessive field length. This can lead to prolonged water application times, which in turn can cause waterlogging, especially at the head ditch end of the field.
- inadequate slope or poor levelling. Low slopes or areas within a field may not allow excessive water to move freely away from a growing crop.
- poor bed formation. Well-formed beds allow cotton roots to grow in soil that is freely drained.
- poor irrigation scheduling. Too frequent irrigations may predispose the crop to waterlogging.
- substantial rainfall after an irrigation event. This could expose the crop to longer periods of inundation.
- long periods of cloudy weather. Low rates of evaporation and reduced radiation (sunshine) may prolong waterlogging.

Impacts of waterlogging on crop yield and quality

Investigations in the early 1980's by the late Arthur Hodgson in Narrabri into the effects of waterlogging, showed that yield of field-grown cotton declined with duration of inundation at each irrigation event. To generate the effects of duration of inundation Hodgson varied the period of irrigation of the crop between 4 and 32 h. However, the degree of yield depression differed between his experiments. When the data of the experiments were combined, yield was strongly related to the number of days when air filled porosity of the soil (proportion of air present in the soil) at a depth of 10 to 20 cm was below 0.1 (i.e. 0.1 cm^3 of air/cm^3 of soil, or 10% air by volume). Lint yield was reduced by 48 kg/ha (0.2 b/ha) for every day of when the soil was low in oxygen (Figure 3.4.1). Hodgson found that there were no further reductions in yield after 96 h (4 days) of inundation across the growing season.

Figure 3.4.1. The relationship between yield and duration of inundation by irrigation from Hodgson (1982)



In field studies starting in the late 90s, also conducted at Narrabri, Bange, Milroy and Thongbai found some contrasting results to those of Hodgson. In some instances where certain agronomic practices were employed, no effects on yield or fibre quality were seen even when the crop had been inundated continuously for up to 72 h (3 d). Field experiments were conducted in which cotton crops were subjected to intermittent waterlogging by extending the duration of irrigations. Investigations compared the timing of waterlogging events, cultivar and landforming (hill height). To generate marked effects of waterlogging on yield it was necessary to reduce hill height. (Hodgson reported reductions in yields with the duration of 32 hours without the need to modify hill height.)

The recent results also showed that waterlogging early in crop growth had far greater influence on yield than waterlogging at mid-flowering or later. The effects of these treatments are summarised in Table 3.4.1.

Table 3.4.1. Different agronomic effects on yield and yield components after waterlogging (up to 72 h inundation)

Agronomic treatment	Maturity	Yield	Final boll number	Final boll size	Fibre length	Micronaire
Hill height (5 cm versus 15 cm)	✗	✓	✓	✗	✗	✗
Variety (Sicala V-2i versus Nucotn 37)	✗	✗	✗	✗	✗	✗
Early waterlogging Pre flowering	✗	✓	✓	✗	✗	✗
Late waterlogging Mid flowering	✗	✗	✗	✗	✗	✗

Source: 1990s studies by Bange, Milroy and Thongbai

The differences in severity of the impact of waterlogging between the two studies could be due to a number of reasons. It is feasible that oxygen levels were not as severely affected by inundation in the more recent experiments because since the 1980s there has been increased awareness within the Australian cotton industry of management practices aimed to maintain good soil structure. As a result, compaction is less severe and less widespread. In addition, there has been considerable improvement of water flow in furrow-irrigated fields through the use of laser-guided levelling systems. Indirect selection of cultivars more suited to the intermittent waterlogging experienced in the Australian growing environments may also have played a role.

Causes of yield reduction due to waterlogging

Waterlogging of cotton has been reported to cause reductions in root growth and nutrient uptake, leaf area and photosynthesis, all leading to restrictions in overall cotton growth and fruiting development.

Results of detailed measurements of crop growth in both the studies of waterlogging mentioned above show that when yield was reduced due to waterlogging it was associated with final boll number being reduced (Figure 3.4.2). Boll size and percentage lint were not affected. Reductions in boll number are commensurate with reductions in growth due to lower radiation use efficiency (amount of dry matter produced per unit of intercepted light), which impacts on the amount of assimilates available for plant growth. Results from these studies also suggested that this reduction in boll number is most likely associated with reduction in fruiting site production rather than increased shedding alone.

The suppression of radiation use efficiency is consistent with the reduction in photosynthesis and the reduced function of photosynthetic enzymes by waterlogging. Reduced concentrations of nitrogen (N) in a leaf can reduce leaf photosynthesis, and the amount of N in leaves is affected by N uptake. Work undertaken by Hodgson and MacLeod (1988) showed that, while leaf N of cotton was reduced due to waterlogging, applying foliar N in the days prior to waterlogging did not fully alleviate the reductions in growth in all cases nor did it rectify the leaf yellowing that occurred. This suggests that other mechanisms, in addition to those acting through the reduced uptake of N, were likely to be acting on leaf performance. The exact reasons for the reduction in photosynthesis and radiation use efficiency with waterlogged cotton are still to be clarified.

In addition to the physiological impacts of waterlogging on the crop there are also significant impacts on nutrient availability and uptake. The availability of N (Figure 3.4.3.), Fe and Zn (reduced) and Mn (increased) are directly affected by the decline in soil oxygen, and uptake of N, K and Fe by the roots is also impaired.

Figure 3.4.2. Results of studies by Bange, Milroy and Thongbai showing the relationship of yield and final boll number influenced by different waterlogging treatments.

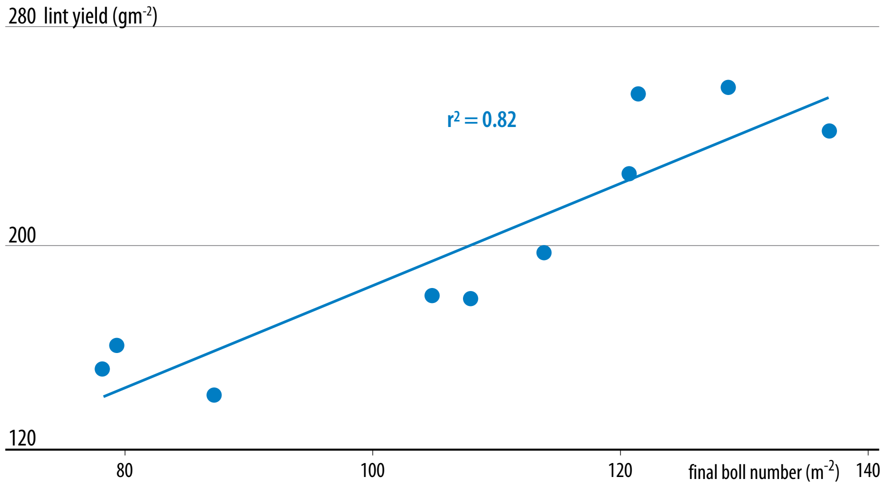
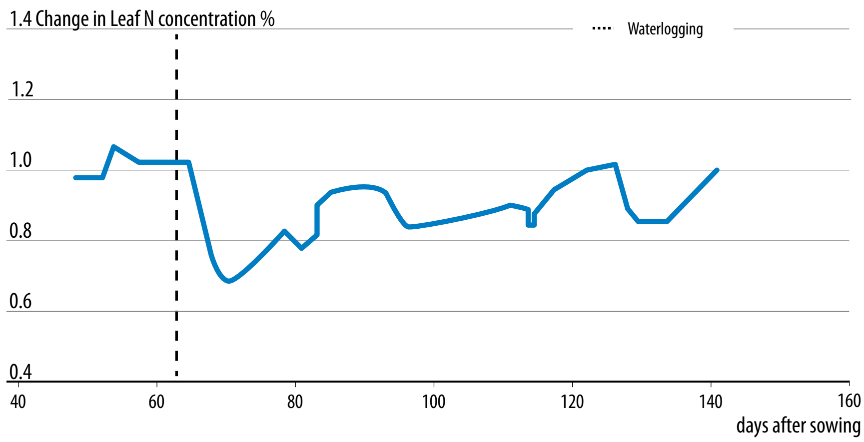
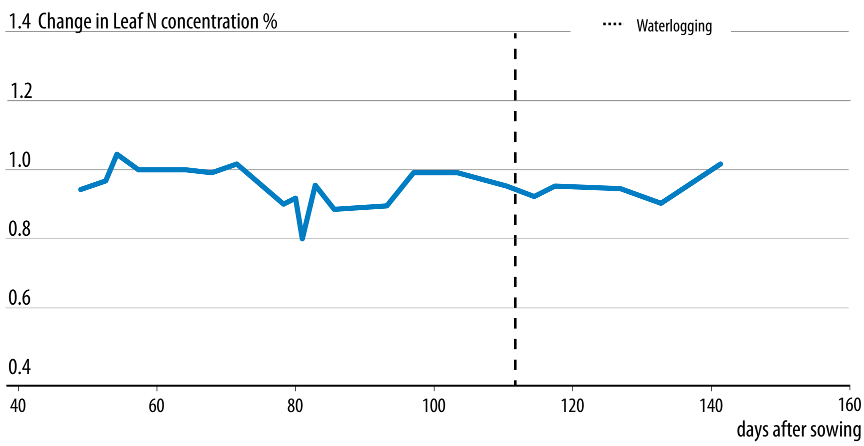


Figure 3.4.3. The impact of waterlogging on the N concentration of the most fully expanded leaf at the top of the plant. The graphs show the change from the non-waterlogged treatment. The heavy dashed line is the waterlogging event and the other lines are normal irrigation events.





Note the large impact caused by the early waterlogging event. (adapted from Milroy, Bange and Thongbai (2009)).

Management options to reduce waterlogging risk

Field design. A uniform slope of at least 1:1500 is best for draining irrigation water or rainfall from a field. Tail drains should also be designed to remove run-off as quickly as possible.

Hill height. Well-formed high beds will decrease waterlogging in an irrigated field.

Irrigation period. Keeping the period of single irrigation events to a minimum will minimise the risk of waterlogging. This can be achieved by assessing irrigation performance and optimising flow rates and irrigation run length to minimise inundation time (see WATERpak Chapter 5.3).

Increasing the water supply capacity may be required where siphon flow rates are increased to get the water on and off the field quickly. In addition, higher system capacity reduces the time it takes to irrigate the whole farm, giving farmers more flexibility to react to climatic influences such as a heat wave or waiting for a forecasted rainfall event.

Foliar fertiliser. Apply 8 kg N/ha just prior to a waterlogging event. Be careful not to use too high rates because foliage may burn. Applications on an already waterlogged field may have little impact. In some circumstances applications of foliar iron (Fe) may prevent leaf yellowing. See NUTRIpak for further details.

Irrigation scheduling. Ensure proper irrigation scheduling. Too frequent irrigations increase the risk of waterlogging. The use of soil moisture monitoring equipment can assist with optimising irrigation scheduling to reduce waterlogging risks and improve yields (see WATERpak Chapter 2.1).

Monitor growth. In some instances waterlogging may induce shedding and if conditions significantly improve and there is adequate nutrition, excessive vegetative growth maybe an issue. Only consider Mepiquat Chloride (Pix) when crops are recovered fully, as the use of this growth regulator may add additional stress, or have no effect.

Monitor weather. If feasible, monitor weather and delay irrigation if there is a high chance of significant rainfall to occur at the time of the scheduled irrigation.

Management of crops following flooding events

The impact of a flood event can range from complete crop failure to reductions in growth and yield. The effect depends on the severity (depth, water quality, flow) and length of inundation. Cloudy weather (low light), coupled with waterlogged soils also causes further impacts on crops. Under these conditions, cotton plants are likely to cease growth (e.g. production of new nodes) and then, as assimilate in the plant becomes limited, shed squares and fruit.

The way the crop is managed for crop recovery may change depending on the timing of these extreme events during the season. If a significant amount of the season remains, then the primary aim should focus on nursing the surviving crop back to a point where it can support new growth. If the flood events have occurred late in the season the focus should be on supporting fruit retention. A crop manager needs to ascertain if there is remaining season length to allow new fruit to be set, develop, and mature before the onset of cold weather.

The time for a new square to produce a flower is on average 23 days while it takes 63 days for a boll on average to develop into a harvestable boll. As the season progresses these times (for nodes, squares and flowers to develop) increase as temperature and light decrease. While new squares can be produced, the risk of these not contributing to final yield is considerable, especially late in the season. In some cases, crops may have reached the point of (or are rapidly approaching) the last effective square that results in the last effective flower. Growers and consultants can determine squares and fruit that are likely to mature using the "Last Effective Flower Tool" in CottASSIST.

For crops to again access to soil water and nutrition, surface roots will need to once again come into contact with oxygen once fields dry out. After this has occurred, the use of leaf testing may provide some guidance as to the plants nutritional requirements. Foliar applications of nitrogen, phosphorus, iron, zinc, and boron may alleviate immediate deficiency symptoms and help nurse plants along. Irrigation schedules may also need to be shortened to avoid stress as overall root function may have been impaired.

Chapter 3 of NutriPAK contains specific information relating to the application of nitrogen and foliar fertilisers, although information concerning nutrient requirements for late season flood affected crops is limited.

Avoid over-fertilising late season flood affected crops as this may induce unnecessary regrowth making defoliation more difficult, delay overall maturity and picking, affect quality, and could lead to pest and disease issues later in the season. Recovering crops can also have delayed maturity and may also inherit pest problems from nearby fields that mature earlier. Be vigilant in sampling recovering crops so that emerging pest issues especially secondary pests such as aphids, mites and silver leaf whitefly are detected early and can be monitored and managed if required.

Further Reading

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3.5 Irrigation and cotton disease interactions

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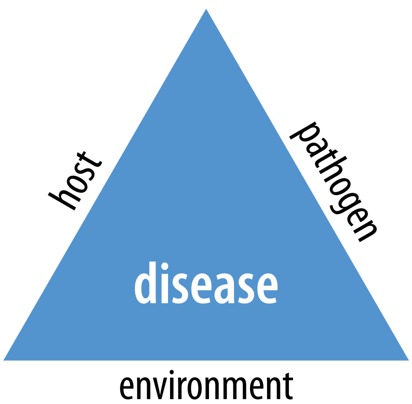
Key points

- Irrigation followed by rainfall and cool weather conditions have contributed to the incidence of Fusarium wilt, black root rot and Verticillium wilt in the Australian cotton industry.
- Irrigation practices can be modified to reduce the incidence of plant disease and their spread within the field and farm.

Plant diseases occur when a virulent pathogen interacts with a susceptible plant host under favourable environmental conditions. These three factors constitute the three sides of the 'disease triangle' and all three must be present for a disease to develop (see Integrated Disease Management Guidelines).

Plant diseases are usually a man-made problem. Irrigated cotton farming systems generally favour the survival and dispersal of the pathogens that cause diseases of cotton and often provide environments conducive to infection. Irrigation practices have contributed significantly to the development of the Fusarium wilt, black root rot and Verticillium wilt problems that are a concern to Australian cotton growers.

The disease triangle



The objective of this chapter is to discuss the positive and negative impacts of irrigation practices on the three components of the 'disease triangle' and to propose possible strategies to minimise the negative impacts on the sustainability and profitability of cotton farming.

The impact of irrigation practices on the pathogen

Dispersal of the pathogen within the field

Dispersal from field to field, that is, introducing the pathogen to new fields

Water moving down a furrow and into and along a tail drain carries soil particles and crop residues. Significant numbers of pathogen spores maybe dispersed in this manner.

Dr David Nehl studied the distribution of spores of the black root rot pathogen in tailwater from an infested field and found 175 spores/litre of tailwater and 11,750 spores/kg of trash carried in tailwater at the tailwater drop-box. Trash carried in tailwater and sampled 2 km from the tailwater drop-box was found to be still carrying 2,671 spores/kg trash.

Figure 3.5.1. Aerial photo of Fusarium wilt showing spread of the pathogen down the furrows.

Aerial photographs of the field distribution of Fusarium wilt also show the significance of spore dispersal in irrigation water. The pathogen that causes Verticillium wilt can be easily isolated from crop residues floating in tailwater return systems.

Repeated wetting and drying cycles reduce pathogen survival

Pathogens survive best in dry soil. Frequent wetting and drying cycles allow for rapid breakdown of crop residues and consequently reduced survival of spores of the pathogen. Many cotton pathogens are favoured by a dry winter period between subsequent cotton crops.

Figure 3.5.2. Large amounts of crop residue are moved about in tailwater return systems.

Various types of 'trashlifter' have been developed to remove a significant proportion of the crop residues from the tailwater return system.

Minimising the impact of irrigation practices on the pathogen

Minimise tailwater and tailwater recirculation by pulling siphons earlier. It is not easy or convenient but it can be done! Less tailwater recirculation means less pathogen redistribution. It is impossible to eliminate stormwater run-off.

> *Trevor Brownlie of "Mahnal" Gibber Gunyah via Theodore writes: "Our irrigation strategy is to irrigate the whole field at once. We operate a two-metre permanent bed system in our Fusarium affected field and therefore only irrigate every second row across the field. However in the 50 to 60 metres of rows surrounding the diseased area we ensure that the siphons are pulled from the head ditch early so that no excess irrigation water reaches the tail drain. This practice has prevented the dispersal of soil particles and infected plant material via the tailwater system. Disease surveys conducted by the QDPI's Dr Joe Kochman have indicated to date that the disease has not spread outside the initial affected area. In addition – any field operation, such as planting, spraying or picking, start at either end of the field and work inwards to the affected area. The rows of the affected area are worked last, and machinery cleaned down before moving on to another part of the farm."*
>
> (Note: When applying this strategy it is essential that the full distribution of the pathogen is known. It may be wiser to minimise tailwater across the whole farm!)

Minimise tailwater backing up into field. This may be achieved by modifying the depth and slope of taildrains and managing irrigations to minimise the volume of water in the tailwater return system.

Remove crop residues from tailwater return systems. Floating 'booms' may be used to hold back rafts of crop residue. Various designs of 'trashlifter' can be installed in the tailwater return system. The potential for natural wetland areas to act as 'biological strainers' is being evaluated.

Flood infested fields for 30-60 days in summer (summer flooding). If water is available and field topography is suitable then summer flooding is an option for reducing, but not eliminating, the pathogen spore population. This has been shown to be effective against black root rot and Fusarium wilt in Australia and is recommended for the control of seedling diseases, black root rot and Verticillium wilt in parts of California. The soil (and crop residues) must be completely submerged.

Consider CPLM or drip instead of furrow irrigation. Centre Pivot/Lateral Move (CPLM) and drip systems should not produce tailwater (from irrigation), therefore reducing the movement of disease causing pathogens from the field.

Beware of contaminated water sources. Run-off from a gin yard may introduce new pathogens. An outbreak of Phytophthora boll rot in California was attributed to the overhead application of water from an infested water storage. Water storages may become contaminated when used to store tail water from fields where a disease is present.

The impact of irrigation practices on the host

Diminished host plant resistance due to waterlogging-induced nutrient imbalances

Natural host plant resistance mechanisms are dependent on adequate host plant nutrition. Potassium is particularly important and potassium deficiency in cotton has been associated with increased susceptibility to Fusarium wilt, Verticillium wilt and Alternaria leaf spot.

Minimising the impact of irrigation practices on the host

Avoid or minimise waterlogging

Fields should have adequate slope and be well drained. Tail drains should be efficient and not allow adjacent areas of the crop to be inundated unnecessarily. For some soil types the use of wide (2metre) beds may provide an alternative system to minimise or reduce waterlogging. Owners of CPLM systems have noted decreased susceptibility to disease which they attribute to reduced waterlogging under these systems. Drip systems should have similar advantages.

The impact of irrigation practices on the crop environment

Irrigations drop soil temperatures

The pathogens that cause seedling diseases, black root rot, Fusarium wilt and Verticillium wilt are all favoured by cooler soil temperatures and adequate soil moisture.

High humidity and periods of leaf wetness favour infection

Foliar pathogens such as those responsible for bacterial blight and Alternaria leaf spot require either very high humidity or periods of leaf wetness for spore germination and completion of the infection process. In the dry Californian climate, the change from overhead sprinkler irrigation (which wet the leaves) to furrow irrigation (where leaves remained dry) provided complete control of bacterial blight. Whilst recent surveys of CPLM users in the Australian cotton industry have not identified an increased incidence of foliar disease under sprinklers, growers are advised to be vigilant as leaf wetness is likely to increase the potential for disease under certain conditions, particularly in wet seasons.

Late season irrigations contribute to later harvests

Later maturing crops are exposed to cooler autumn weather which is more favourable for disease development. Irrigations can contribute to fluctuating humidity in rank cotton which can lead to Sclerotinia outbreaks. This can happen when ideal weather conditions occur simultaneously with a particular plant growth stage (dying petals and leaves). Spores from the apothecia are forcibly ejected when relative humidity changes and can infect bolls and fruiting branches when dying petals and dead leaves get hung up in the canopy. Withholding the final irrigation to cotton fields in California resulted in a lower incidence of Verticillium wilt and a higher yield than in control fields that did receive the final irrigation.

Minimising the impact of irrigation practices on the crop environment

- Plant into moisture in preference to watering-up.
- Avoid late irrigations.
- Be vigilant for foliar disease outbreaks under sprinkler systems, particularly in wet years.

Conclusions

Irrigation strategies have contributed, and are still contributing, to the emergence of significant cotton disease problems that threaten the economic viability of cotton farming. Cotton plant breeders may eventually provide solutions to these disease problems in the form of resistant varieties but it could be a long time before that solution is forthcoming. In the meantime it is essential that growers do all they can to slow the rate of epidemic development by reducing the spread of pathogens, providing for the adequate nutrition of the host and by manipulating the crop environment so that it is less favourable for disease development.

Further reading

For further reading, see *Integrated Disease Management Guidelines*

Section 4

Irrigation management of grain crops

4.1 Irrigated wheat – best practice guide

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Key point

- Seasonal water requirement varies from 360 to 550mm
- A full irrigation strategy or limited water irrigation strategy can be used
- The period leading up to and including flowering is the most sensitive to water stress.
- Good agronomic practices are needed to maximise production and minimise lodging risk
- Starting soil-N determines the most appropriate nitrogen strategy
- Durum out yields bread wheat and quick maturing varieties with good lodging resistance should be used
- Adjust row spacing to manage biomass and tillering – 30cm row preferred
- Aim to establish 100-150 plants/m^2 of bed or hill area
- Planting on rainfall preferred over pre-irrigation and watering up which can delay planting and produce excessive biomass respectively
- Irrigate to encourage secondary root development if needed
- Use plant growth regulators to minimise lodging
- Use disease resistant varieties and a pre-planned fungicide application strategy

Plant Water Use

The amount of water required to produce a wheat crop with maximum yield is not a fixed value as temperature and relative humidity during the growing period along with wind and soil moisture all determine the rate of evaporation from the soil and transpiration from the plant (evapotranspiration or ET_c). In favourable seasons the water requirement may be as low as 360 to 440 mm whereas in a warmer dry year this requirement could be up to 480 to 550 mm to produce maximum yields. Table 1 summarises the results of APSIM simulations for wheat yields and evapotranspiration water use in the Northern Grains Region.

The DAFF Queensland free on-line tool CropWaterUse can be used to examine the seasonal variability in crop water requirement for fully irrigated wheat at your location (see Table 2).

It shows the irrigation demand for 1 June planted wheat at three locations (Narrabri, Dalby and Emerald), assuming that the crop was fully-irrigated to target maximum yield. An irrigation application efficiency of 75% and a 75mm irrigation target deficit are assumed. Results show a large variation in seasonal crop water demand, rainfall and irrigation demand between locations and season types.

Figure1 shows the daily water use in wheat which peaks during flowering and milk development (GS60 to GS70).

Moisture availability at this stage is critical to the yield of the crop. Moisture stress for more than a few days during this period will result in lower grain yield and quality.

The area of irrigated wheat to plant is a function of wheat price, available water and your planned irrigation strategy.

Irrigation Strategies

Full Irrigation

For fully-irrigated wheat (with a target yield exceeding 8 t/ha) where water is not limited, the aim is to maximise yield by scheduling irrigations to match crop water demand and avoid crop stress during the entire growing season. This requires the close monitoring of soil moisture once secondary root development has been completed (normally GS31).

In order to avoid crop stress, do not allow soil water to fall below 50% of plant available water capacity (PAWC). This is commonly referred to as the 'refill point'.

Table 4.1.1 Range of simulated maximum yield (t/ha) and evapotranspiration water use for 90% of years[1], for quick maturing irrigated wheat (Kennedy) on 2m beds in the Northern Grains Region, in the absence of lodging, disease, pest and frost damage

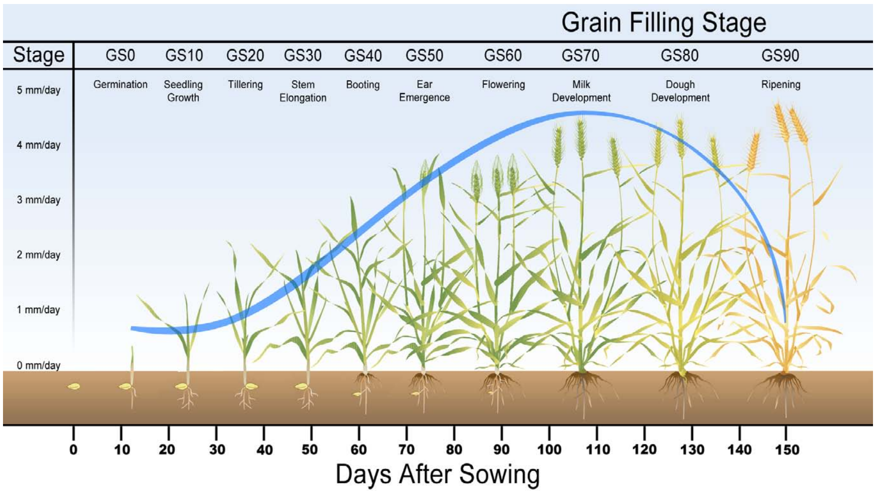
Location	Range of Maximum Yield (t/ha)	Range of Maximum Evapotranspiration water use (mm)
Emerald	6.2 – 7.8	360 – 480
Dalby	7.0 – 9.5	430 – 550
St George	6.4 – 8.2	360 – 480
Goondiwindi	6.8 – 8.7	410 – 490
Walgett	6.7 – 8.3	420 – 500
Gunnedah	7.6 – 9.6	440 - 540

[1] (excludes the top 5% and bottom 5% of years). Source: A. Peake

Table 4.1.2 Comparison of average water requirements for wheat planted on the 1 June at Narrabri, Dalby and Emerald, based on historical weather data (1957 to 2008)

	Narrabri			Dalby			Emerald		
Season Type	Dry	Ave	Wet	Dry	Ave	Wet	Dry	Ave	Wet
Crop ET_c (mm)	403	378	351	432	407	385	536	517	494
In-crop Rainfall (mm)	119	210	335	104	173	258	50	111	231
Irrigation Demand (ML/ha)	3.7	2.6	1.6	4.2	3.3	2.5	6.1	5.2	4.4
No. of Irrigations	4	2	2	4	3	2	6	5	4

Figure 4.1.1 Wheat water use pattern and critical growth stages



Once below 50% of PAWC, crops use more energy extracting the remaining soil water. Plant growth and yield potential will fall considerably if soils are allowed to dry down beyond this threshold.

Make sure water is available for 2 to 3 days before the crop reaches its refill point. The reproductive growth phase typically coincides with an increase in temperature and an acceleration of plant water use. Any delay in water application can cause significant yield losses.

The period leading up to and including flowering is the most sensitive to water stress. Stress at this time will reduce the number of heads per plant, head length, and number of grains per head. It can also restrict root growth. Yield losses from excessive water deficits at this time cannot be recovered by later irrigations.

Key points to consider when scheduling irrigation for fully-irrigated wheat are:

- crop stress must be avoided. ET_c is usually linearly related to crop yield. Stressing the crop at any stage of development reduces ET_c and yield. This yield loss cannot be recovered by irrigating at a later time. To avoid crop stress, it is important to know when to irrigate and how much water to apply. Table 4.1.3 summarises the water management considerations for each growth stage of wheat.
- The application of a fixed water depth at each irrigation can lead to deep drainage losses. It is not necessary to refill the soil profile at each irrigation. Overhead systems are especially suited to application of small irrigation depths, but application depths can also be reduced with surface irrigation systems by increasing siphon flow rates and reducing irrigation runtimes.
- Crops can only extract water from their effective root zone. Therefore, the depth of soil wetted by irrigation needs to be adjusted during the season to respond to increases in root zone depth and irrigation wetted front should not go deeper than the effective crop root zone.
- The soil water deficit to trigger irrigation also depends on the depth of the root zone and needs to be adjusted during the season. Both the ET_c rate and the soil water deficit change daily, so irrigation frequency needs to be adjusted in response to these changes.
- The desired soil water deficit and the irrigation frequency also depend on the irrigation system capacity (mm/day). This highlights how much water the irrigation system can apply in one day, allowing for system breakdowns or maintenance. The greater the system capacity, the greater the soil water deficit that can be replenished quickly.

Irrigations can be scheduled based on soil moisture monitoring using one of the commercial soil moisture monitoring tools available. This equipment can tell you the rate of crop water use and the depth of water extraction.

This can be used to make irrigation scheduling decisions.

Irrigation can also be scheduled based on estimation of crop ET_c from weather data. WaterSched2, a free online irrigation scheduling tool developed by DAFF Queensland is now available. This tool automatically downloads daily weather data from different locations in Queensland and New South Wales and, using farm-specific inputs, conducts a daily soil water balance and economic analysis to determine when and how much to irrigate.

Figure 4.1.2 is an example of the end of season report generated by WaterSched2 for a fully irrigated wheat crop at Dalby in the 2009 season. This report summarises the water, crop and economic data for the crop. It provides the WUE indices for predicted and actual yield achieved. The graph at the bottom of the report shows the daily soil water depletion during the season.

During the season this report provides the information needed by the grower to decide on their most appropriate irrigation scheduling strategy in response to crop water requirements, likely economic returns and whole farm water availability.

Correct timing of the last irrigation will ensure adequate grain fill and also reduce the risk of lodging and harvesting delays. It should be applied around mid dough growth stage (GS80) if readily available water has been used to 60 to 90cm soil depth.

Table 4.1.3 Critical water management considerations by growth stage for wheat

	Zadoks Development Stage	Water Management Consideration
0	**Germination**	Adequate soil moisture essential to establish desired plant population. Waterlogging can increase seed mortality
1	**Main stem leaf production** Seedling Stage is the growth stage from wheat emergence until the plants begin to tiller	Early weed control will conserve plant available water.
2	**Tiller production** Tillering usually starts when the plant has 3- 4 leaves. A (short growth cycle) wheat plant will typically produce 7-8 leaves on the main stem before stem elongation occurs.	Early weed control will conserve plant available water. Good nutrient and water supply are determining the potential number of heads produced by the crop.
3	**Stem elongation** Main stem node production. The maximum potential number of florets (and therefore maximum yield potential) is now set. The tillers produced last during stem elongation will often die. The final number of productive tillers depends on the conditions.	Good nutrient and water supply are determining yield potential. If stress during stem elongation is followed by heavy water application, wheat has the ability to produce new tillers and additional heads. However these additional heads will delay harvest and the risk of losses from lodging and non-uniform ripening usually increases. Soil water depletion should not exceed 50% of PAWC
4	**Booting** By booting each plant should have 2-3 productive tillers depending on growing conditions and crop density.	Water stress will significantly reduce yield. Soil water depletion should not exceed 50% of PAWC.
5	**Heading** The spike (also called the head or ear) is emerging from within the flag leaf.	
6	**Flowering** Pollen is being released and the individual grains are being fertilized.	
7	**Grain milk stage** When the grain is squeezed, a milky solution is apparent.	
8	**Grain dough stage** When squeezed, the grain will still deform slightly, but no liquid is apparent.	Yield is almost set, but water stress will still reduce grain size and yield. Soil water depletion should not exceed 50% of PAWC.
9	**Ripening** Grain is hard and firm and ready for harvest. Grain is best harvested at 14% moisture content. Wetter grain (>14% moisture content) has storage problems.	Lodging will reduce harvestable grain yield.

Source: CIMMYT International Maize and Wheat Improvement Center, 2012

Figure 4.1.2 WaterSched2 End of Season Field Summary report for a fully irrigated wheat crop at Dalby in 2009

WaterSched2

Report Compiled By:
Jose Payero
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End of Season Summary

Field Summary

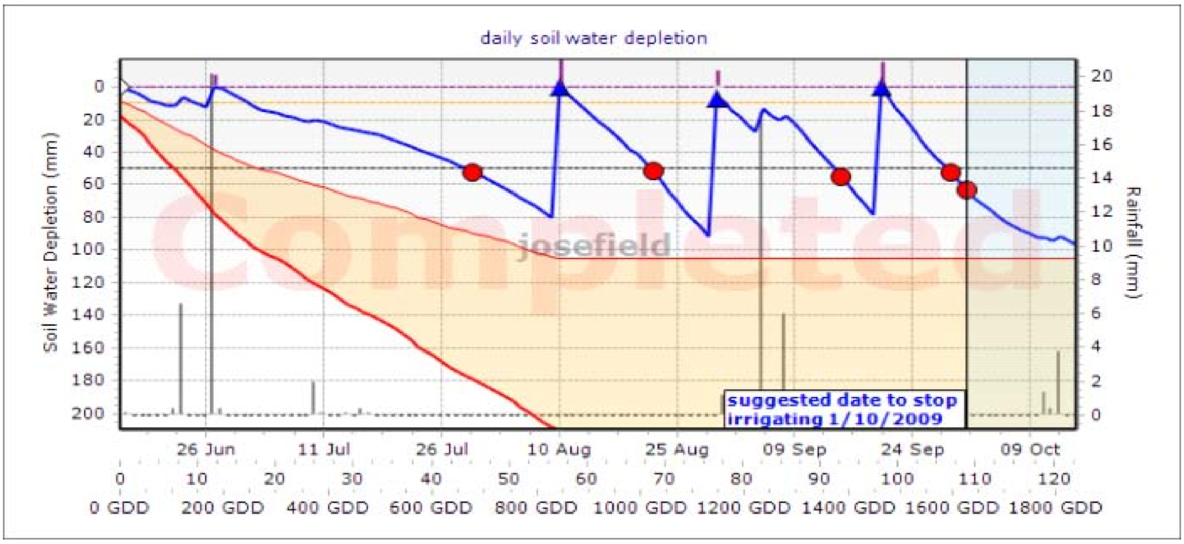
Farm:	josefarm	**Plant Date:**	15/06/2009
Location:	Dalby	**Season:**	2009
Field Name:	josefarm	**Length of Season:**	123 days / 1839 GDD
Field Size:	100 ha	**Irrigation Type:**	Sprinkler 100%
Crop:	Early Wheat	**Irrigation Trigger Deficit:**	50 mm

Water Summary / **Crop Summary**

	mm	ML/ha		
Total Irrigation:	300	3	**Expected Yield:**	8 tonnes/ha
Total Rainfall:	62	0.62	**Predicted Yield:**	8 tonnes/ha
Total Losses:	49	0.49	**Actual Yield:**	6 tonnes/ha
Starting Soil Water:	210	2.1	**Accumulated ETp:**	409 mm
Ending Soil Water:	113	1.13	**Accumulated ETc:**	409 mm
Soil Water Change:	97	0.97	**Economics Summary**	
Total Water Input:	459	4.59	**Price Per Unit:**	$255 / tonnes
Net Water Supply:	409	4.09	**Variable Costs:**	$808 / ha
			Gross Margin:	$722 / ha

Water Use Efficiency

	Predicted	Actual	Gross Margin
Total Water Use Index TWUI	1.74 tonnes / ML	1.31 tonnes / ML	$158 / ML
Gross Production Water Use Index GPWUI	1.96 tonnes / ML	1.47 tonnes / ML	$177 / ML
Irrigation Water Use Index IWUI	2.67 tonnes / ML	2 tonnes / ML	$241 / ML
Crop Water Use Index CWUI	19.55 kg / mm	14.66 kg / mm	$1.76 / mm



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Limited Water Strategies

If there is a high probability of reduced water allocation and insufficient rainfall then the yield target may need to be revised down and supplementary irrigation strategies adopted. Supplementary irrigated crops are 'water limited' – there is not enough water available to fully irrigate the area to be sown. Growers faced with this situation have two main choices:

1. maximise production from the water available
2. grow the largest area possible where a single in-crop irrigation can be applied.

Growers wanting to maximise productivity per ML of water should consider growing a smaller area of crop and matching crop water demand to achieve a high yield. This strategy avoids the extra costs associated with growing a larger area. In general, maximum crop productivity under irrigation is achieved when good soil moisture is available at sowing and then one or two supplementary spring irrigations are applied (one irrigation in wetter districts such as the Liverpool Plains, and two irrigations in drier areas such as Emerald and Goondiwindi).

If a large area of wheat must be planted as part of a rotation, and only a single irrigation is possible, the best timing is one which applies water at the most critical growth stage – from stem elongation though to flag-leaf emergence.

Table 4.1.3. summarises the impact of water stress on wheat at different growth stages.

APSIM simulations suggest that the best timing for a single in-crop irrigation of around 1 ML/ha is from early stem-elongation through to flag-leaf emergence. It will still have time to help the crop develop a little more biomass, yet will also leave some soil water for flowering and early grain filling. This recommendation is based on 40 years of weather data. The best timing of a single irrigation within a particular season will vary depending on the timing of in-crop rainfall, and stored water at sowing.

If two irrigations (or 2ML/ha) is budgeted, then an irrigation applied at early to mid-stem elongation and again between flag-leaf and flowering is recommended.

Agronomy

To achieve high irrigated yields it is also necessary to follow good agronomic practices.

Crop lodging is a potential risk when targeting high wheat yields. Lodging occurs mostly after ear emergence and can significantly affect grain yield and quality. Factors affecting lodging potential include:

- variety lodging susceptibility;
- shallow root systems due to abundant soil moisture or frequent irrigations;
- subsoil constraints like sodicity or compaction;
- high nutrition levels causing plants to grow too quickly; and,
- severe weather during crop ripening.

The range of agronomic practices discussed below is aimed at maximising yield and controlling lodging through canopy management.

Nutrition

Test soil for starting nitrogen (to 90cm depth) and phosphorus (to 20cm depth) in April/May before sowing. Long fallow paddocks with high soil-N require careful management of canopy growth from establishment to avoid lodging. Paddocks sown straight after cotton (low soil-N) are ideal to target maximum yield and manage early season canopy.

At least 275 kg N/ha is required to grow 8 t/ha of wheat. The success of nitrogen application depends on soil type, irrigation system, sowing soil moisture and rainfall and temperature at tillering. Nitrogen can be split applied in low soil-N paddocks (some fertiliser will be required at sowing). In high-N soils nitrogen fertiliser requirements are more safely applied at stem elongation (GS31) – ideally before a rainfall or irrigation event.

In low soil-N post-cotton paddocks, starter fertiliser containing 10-20 kg P/ha will improve establishment.

Variety Choice

On average durum wheat has consistently yielded 1 t/ha higher than bread wheat in northern irrigated wheat trials. In 2011 the durum varieties Bellaroi and Caparoi provided the highest yield potential and lodging resistance. The durum variety Hyperno has high yield potential but was found to be prone to lodging. Quick maturing varieties such as Kennedy and Longreach Crusader are the most likely APH bread wheat varieties to achieve high yields, although Longreach Crusader has shown significantly more lodging resistance than Kennedy in high-N paddocks.

Row spacing

Row spacing can be altered to manipulate vegetative biomass and tillering. In low soil-N paddocks the most appropriate row spacing is 30cm, or 6 rows on a 1.8 metre bed. Wheat performs best at 30 cm row spacing as it responds well to plants being more evenly distributed across the bed.

In high soil-N paddocks wider row spacing will increase intra-row competition, reduce tillering, and assist in the regulation of early season biomass during tillering.

Plant population

A plant population of 100-150 plants per square metre of bed or hill area is ideal in the northern region. Low plant populations of 50-100 plants per square metre of bed can achieve high yield levels but plants do not establish evenly.

Seedbed Preparation

Seedbed preparation has a significant impact on seedling emergence and yield potential. Following pupae-busting, tillage should be used to prepare a new seedbed that is free of clods and cotton stubble. Seedbed tilth needs to be in an optimum condition for seed placement and emergence.

Planting Date

Planting time is a management compromise that balances having the crop flowering soon after the last heavy frost, but still early enough to allow adequate grain fill before the heat in spring.

Varieties differ in the time they take from planting to flowering. Select the planting time for your variety that ensures it will flower after there is little chance (I in 10 years) of a frost occurring.

Sowing early within the optimum range is better suited to low-N paddocks where canopy can be managed through delayed N application, and when irrigating up.

Planting late (within the optimum range) is an alternative strategy to reduce lodging in high soil-N paddocks.

Establishment

Ideally wheat should be planted after a rainfall event which provides planting moisture and ensures seed germination and establishment. This provides the best opportunity to achieve high yields (particularly if starting soil N levels are low). In this situation a uniform plant stand can be achieved and you can manage early season canopy growth and allow an irrigation to ensure secondary root development.

Pre-irrigation is risky as sowing can be delayed if rain occurs. However, establishment can be better in this scenario than if a paddock is dry-sown and watered up.

If the profile is completely dry at planting the only option may be to plant shallow and water-up. This is the least desirable option, particularly if starting soil-N levels are very high. Often, in water-up situations, plants still do not initiate secondary root growth and require further irrigation during tillering which can result in excessive early season biomass. This can predispose the crop to lodging, particularly where soil starting N levels are high.

Secondary Root Growth

Assess soil moisture status at 25-30 days after emergence. If there is dry soil below the sowing depth of seed, apply an irrigation to encourage secondary root development on low soil-N paddocks. Early secondary root development will enhance water and nutrient uptake.

Plant Growth Regulators

Use of plant growth regulators (PGRs) to minimise lodging is still being researched for irrigated wheat. Their use is recommended in high soil-N paddocks where canopy growth is excessive. Check and follow label registrations and instructions.

Disease Management

A pre-planned strategy of fungicide applications based on growth stage and emergence of the top three leaves provides greatest marginal returns when susceptible wheat cultivars are subject to disease.

Where disease onset is early or where susceptible varieties are grown with no up-front protection an application at GS31-32 may be needed. One application at GS39 may be sufficient.

Consider an additional ear-emergence fungicide where stem rust is the primary disease target.

Consider a first-flower spray where wheat or durum is at high risk of Fusarium head blight.

More specific information is also available on root and crown diseases and stripe rust and septoria tritici blotch in irrigated systems.

Further Reading

Lacy, J and Giblin, K 2006 Growing eight tonnes a hectare of irrigated wheat in southern NSW NSWDPI

Sykes, J. 2012 Irrigated Wheat: Best Practice Guidelines in Cotton Farming Systems, Cotton CRC

4.2 Irrigated sorghum – best practice guide

Trev Philp
Pacific Seeds

Graham Harris
DAFF Queensland

Key point

- Water required varies from 400 to 850mm
- Sorghum has a high demand for nitrogen, phosphorus and potassium
- Full season maturing hybrids use more water but have higher yield potential
- Planting date affects water use
- Narrow row spacing out-yield wider rows (1 metre and greater)
- Use populations of 100,000 to 150,000 plants/ha
- Waterlogging can reduce yields by 0.2 t/ha/day of waterlogging
- Irrigation timing is determined by available water supply – full irrigation and limited water strategies are used

Plant Water Use

The amount of water required to produce a sorghum crop with maximum yield is not a fixed value as temperature and relative humidity during the growing period along with wind and soil moisture all determine the rate of evaporation from the soil and transpiration from the plant (evapotranspiration or ETc). In favourable seasons the water requirement may be as low as 400 to 450 mm whereas in a hot dry year this requirement could be up to 700 to 850 mm to produce maximum yields. The DAFF Queensland free on-line tool CropWaterUse can be used to examine the seasonal variability in crop water requirement for fully irrigated sorghum at your location.

Table 4.2.1 shows an example of the information that CropWaterUse can produce. It shows the irrigation demand for 15 September planted grain sorghum at three locations (Narrabri, Dalby and Emerald), assuming that the crop was fully-irrigated to target maximum yield. An irrigation application efficiency of 75% and a 75mm irrigation trigger deficit are assumed.

Results show a large variation in seasonal crop water demand, rainfall and irrigation demand between locations and season types.

Figure 4.2.1 shows the typical daily water use pattern for grain sorghum, which peaks during the late boot to early flowering stage.

Moisture availability at this stage is critical to the yield of the crop. Moisture stress for more than a few days during this period will result in lower grain yield and quality. Standability can be affected where severe moisture stress is encountered in the 2 weeks after flowering.

The area of irrigated sorghum to plant is a function of sorghum price, available water and your planned irrigation strategy. If there is a high probability of reduced water allocation and insufficient rainfall, then you may need to consider revising down your yield target and adopting limited water strategies. If water is limited, you can:

1. Plant the area as a raingrown crop
2. Plant more area than can be fully irrigated and then deficit irrigate the crop, or
3. Reducing the area planted and fully irrigating the crop

A fully-irrigated crop is irrigated to completely meet crop water demand that is not met by rainfall and soil water storage. On the other hand, deficit-irrigation occurs when the full crop demand for water is not satisfied, and can be a useful strategy to maximise the potential upside from improved seasonal conditions.

Table 4.2.1 Comparing of water requirement for grain sorghum planted on the 15 September at Narrabri, Dalby and Emerald, based on historical weather data (1957 to 2008)

	Narrabri			Dalby			Emerald		
Season Type	**Dry**	**Ave**	**Wet**	**Dry**	**Ave**	**Wet**	**Dry**	**Ave**	**Wet**
Crop ET_c (mm)	639	608	577	589	565	551	669	644	622
In-crop Rainfall (mm)	137	232	364	171	265	361	154	221	367
Irrigation Demand (ML/ha)	6.3	5.2	4.1	5.6	4.2	3.2	6.8	5.6	4.7
No. of Irrigations	6	5	4	5	4	3	6	5	5

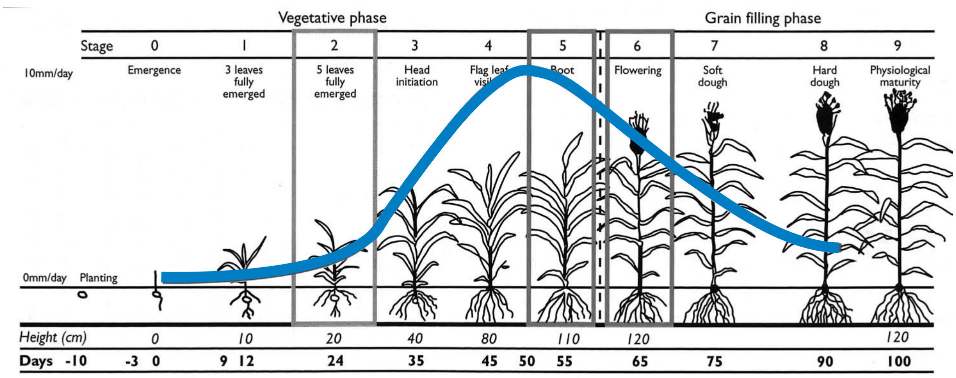
The limited irrigation water should be applied during the most water stress sensitive growth stages of the crop. Therefore, irrigation may be withheld during early vegetative stages (until 6 to 8 leaves) and the late ripening period. The aim of deficit irrigation is to maximise irrigation water productivity rather than achieving maximum yields.

The feasibility of these strategies depends on how much water is available from in-crop rainfall and stored soil water and whether the raingrown yield produces acceptable profits at that location. In such situations it would be advantageous to plant as much area as possible. However, in a dry environment, planting more area that can be effectively irrigated can result in crop failure and financial loss.

Another point to consider is that to maximise profits of the whole farm, it is important to prioritize the allocation of water to those crops that have a higher return per unit of the limiting factor (either land or water). Therefore, even though enough water may be available to grow a fully-irrigated sorghum crop, it may be more profitable to save the water to grow an alternative summer crop or winter crop.

These types of economic decisions require complex analysis. For assist in this decision making, a free online tool called Irrigation Optimiser has been developed by the Agricultural Production Systems Research Unit. This tool makes it easier for farmers to decide which crops to plant and what irrigation strategies to implement to achieve maximum whole of farm profitability.

Figure 4.2.1 Grain sorghum water use pattern and critical growth stages



The Irrigation Optimiser is very easy to use allowing farmers to input information specific to their own farm enterprise to answer crucial questions about how to maximize farm profits given the volume of water and area of land available for any individual operation.

Nutrition

Sorghum is potentially a very productive crop and as such can place high demands on soil nutrient supplies.

For instance, studies have shown that a sorghum crop yielding 7t/ha would require around 215kg of nitrogen, 25kg of phosphorus, 170kg of potassium and a balance of trace elements. Adequate supplies of nutrients in the correct proportion are essential for normal crop development and maturation. A nutritional deficiency or imbalance invariably increases the duration of sorghum growth, thus increasing susceptibility to midge attack and increasing moisture usage.

Studies have shown that N, P, K uptake by sorghum is greatest during the rapid vegetative (G.S.1) growth period and during the grain formation stage (G.S.3). The period from emergence to floral initiation has the greatest influence on potential grain yield as head size and tiller number is established during this period. Since the potential yield is set at the time of head initiation (6 to 8 leaf stage), the plant should have optimum growing conditions at this time, although when water is limited it is more important to minimise water stress at flowering.

Maintenance of adequate nutrition after floral initiation is essential to maintain the potential grain number already determined and to increase the protein content of the grain.

Nitrogen (N)

Sorghum takes up 75% of its nitrogen requirement in the vegetative period prior to floral initiation. A shortage of nitrogen during this period significantly reduces growth in stems and leaves and consequently in the number of flowers produced and so leads to a reduction in yield. For the remaining nitrogen demand, that taken up between flowering and maturity is most important, for a shortage of plant available nitrogen during this period results in large reductions in the protein content of the grain.

Nitrogen fertilisers are best drilled into the beds prior to planting as germination is severely reduced if nitrogen is in direct contact with the seed. Applications with seed contact are limited.

Split applications may be preferable if there are reservations as to the future water supply or substantial rates are to be used.

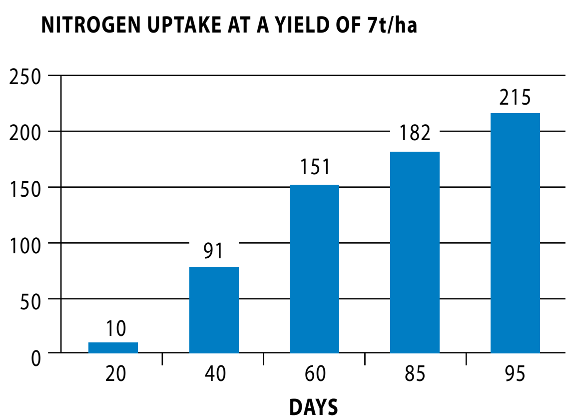
Side dressings applied at the boot stage have produced significant yield and protein increases when insufficient nitrogen has been applied at planting.

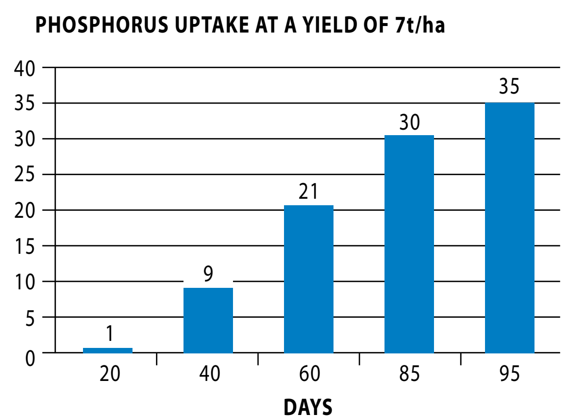
It has been suggested that less total nitrogen is needed with side dressings if two thirds is applied at planting and one third at the boot stage.

Irrigated sorghum will access between 70-80% of its total nitrogen requirement from the top 60cm.

Soil testing and nitrogen recommendations should be based on subsoil results concentrating on the top 60cm. Dryland crops will access deeper nitrogen as they chase water if available.

Figure 4.2.2 Nitrogen and phosphorus uptake patterns for grain sorghum





Phosphorus (P)

Phosphorus is vital for the early development of young sorghum. It is an essential component of substances which manufacture sugars and proteins in the plant. The uptake of phosphorus peaks at early flowering, with 45% of the total phosphorus demand being taken up during booting and flowering. A phosphorus deficiency in sorghum leads to restricted root development and delayed flowering and maturity.

Phosphorus is best applied as a band at planting so that seedlings have immediate access to the element.

Sorghum crops will only respond fully to applied nitrogen if the soil phosphate is adequate and readily available.

Early planted spring crops, growing in cool conditions, will often respond to phosphorus even if soil phosphate tests are good. Recent studies into phosphorus and sorghum have identified that sorghum is susceptible to long fallow disorder. Due to enforced long fallows, yield responses to phosphorus fertilisers are becoming more common. Another side effect of utilising stored soil moisture is the possible redistribution of nutrient to the surface, where its remains unavailable for much of the season. Average yield responses to seed applied phosphorus have been around 400kg/ha. This is probably best applied by an ammonium phosphate (DAP, MAP or a proprietary Starter).

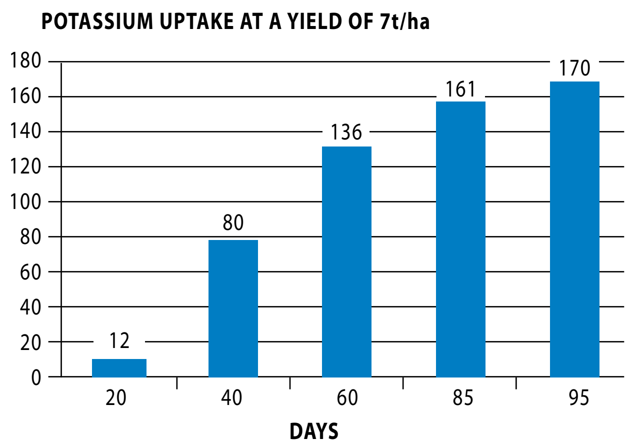
The 'pop-up' effect (the fast start given to seedlings in cool conditions by phosphorus fertiliser) does not appear as clear cut in sorghum as in corn.

Phosphorus responses are likely when soil P levels are less than 15 ppm.

Potassium (K)

Potassium is taken up in large quantities by the sorghum plant. Potassium plays a major role in the water relations within the plant and increases vigour, disease resistance and grain quality. Sorghum takes up 50% of its potassium requirements during the vegetative period prior to floral initiation. Adequate supplies of potassium are therefore essential in the establishment of a healthy stand of grain sorghum.

Figure 4.2.3 Potassium uptake pattern for grain sorghum



Zinc (Zn)

Zinc, although required in relatively small amounts, is essential during the development of the young sorghum plant. A zinc deficiency which most commonly occurs on alkaline soils can greatly delay flowering and maturity. Yield potential is also depressed by zinc deficiency. Soil tests give some indications as to soil zinc status but best judgements are from visual symptoms and/or leaf analysis. Zinc can be applied as a foliar when the problem is noticed but by the time the yield depression is under way the treatment is really only a correction. Zinc applications as foliar sprays should be applied within four weeks of emergence. Prevention is better than cure and any suspicion of zinc deficiency should be counteracted by one of the various soil applied zinc formulations. The oxide and sulphate monohydrate forms should be applied twelve weeks before planting if the crop is to derive any benefit from it.

Establishment

Variety Choice

Variety maturity determines the duration of the growth period, which coupled with daily evapotranspiration, determines the total water requirement of the crop. Thus sorghum of different maturities requires different amounts of water for optimum production. A full season late maturing hybrid will use more water and nutrients than a quick season hybrid but longer season hybrids may have higher yield potential.

Planting Date

Typical optimum early sowing times in cotton growing districts are late September to early October. Emerald is the exception as sowing can begin in mid August through to the end of September and then recommence In January through to mid February. Soil temperatures at the spring planting time are normally rising (taken at 8am at planting depth) and temperatures of 16 to 18°C are ideal for spring plantings.

Planting as early as agronomically possible will provide a number of benefits:

- increased water use efficiency, by avoiding yield loss from heat
- maximise tillering and leaf production
- lessen the risk of yield loss from sorghum midge
- reduce the influence of heat at flowering
- higher yields compared to later plant.

Late plantings in summer should be timed to complete flowering before diurnal temperatures fall below 18°C (day) and 13°C (night) as temperatures below these may result in reduced seed set.

Sorghum is sensitive to frosts so grain fill should be completed before the first severe frost.

Row spacing and plant population

Overhead sprinkler irrigation lends itself to any combination of row spacing from narrow rows 15 to 20cm apart to wider rows up to one metre apart. Wider rows can allow inter row cultivation for better weed control, however experience and trial work has shown that evenly spaced narrow rows have a yield advantage over wider rows.

With surface irrigation in furrows, the situation is slightly different. In trials conducted at Emerald comparing single rows one metre apart at 120,000 plants per hectare and twin rows 40cm apart on one metre beds, the single rows yielded 7.0 t/ha while the twin rows yielded 9.2 t/ha.

Narrow rows at populations of 80,000 to 150,000 allow for higher rates of tillering, which allows for compensation and yield increase if seasonal conditions are better than expected. In situations where stress pre-flowering reduces viable tiller numbers, higher populations will yield more if water supply is adequate through flowering and grain fill.

If the surface irrigation system allows and the soil type is suitable, two metre beds with four to six rows on the bed have proved very successful with plant populations up to 150,000 per hectare.

Higher populations yield more if stress occurs post flowering. Recent trial work demonstrates a very flat response curve under full irrigation and optimum populations would be 120,000 at 1m rows and 140,000 at 75cm rows.

Plant populations on the higher end may be an advantage for management with detail to high water and nutrition inputs.

Some hybrids have reputations as low population hybrids. This may occur where a hybrid has a high ability to tiller as varieties with tillering ability can be planted at lower densities.

Seed companies can provide recommendations of plant populations for each hybrid.

Irrigation Management

Irrigation System

Irrigated grain sorghum is produced under two main systems – surface irrigation or overhead sprinklers.

Surface irrigation can be by furrow or bays where the water is applied by syphons, gated pipe or various types of check valve systems.

Overhead sprinklers systems range from the large centre pivot and lateral moves to hand shift pipes and travelling irrigators.

All have their advantages and disadvantages and certain soil types are more suitable to one system over another. However, when looking at setting up an irrigation system such things as topography, soil types, water supply, water infiltration rate, evaporation rate, potential crop types and of course cost all have to be considered.

When using furrow irrigation, the duration of each watering or the time of inundation can have a major impact on yield. If watering time is prolonged and water logged conditions result for more than 24 hours at each irrigation, yield losses of up to 50% have been recorded compared to non water logged areas. Rule of thumb is 0.2t/ha/day of waterlogging lost.

However, be careful using time as a measure of an irrigation's efficacy, as soil type, length of the field, the slope, the flow rate and the deficit of each field is different.

When the soil becomes waterlogged following long periods of surface irrigation, nitrogen uptake by the plant is reduced and nitrogen is lost from the soil through leaching and denitrification. To minimise yield losses when surface irrigating, the crop should be irrigated quickly and evenly and then drained rapidly to reduce the duration and severity of the water logged soil condition.

Field layout and irrigation management are main causes of waterlogging of irrigated crops. Most of the irrigation in Australia occurs on medium to heavy clay soils with slopes less than 2%. Generally these soils have a very good water holding capacity, but have slow infiltration rates and slow drainage rates. These soil types waterlog easily under the wrong type of management. Generally clay soils with slopes of less than one percent should not exceed furrow lengths greater than 500m.

However, through good bed/row preparation, head ditch layout, and the use of lower soil water deficits, flat paddocks can be managed effectively.

Furrow irrigation efficiency is maximised where fields are professionally levelled.

Crop Water Use Efficiency

Grain sorghum is a very water efficient crop and is more tolerant to stress than maize. Sorghum is capable of very high water use efficiency, but under cooler environments with good water supply, maize will produce more grain per mm of crop ETc. Sorghum CWUI ranges between 10 to 25 kg/mm depending on stress levels and management. With careful management and today's hybrids, 25 kg/mm is possible.

For maximum yields the available water in the active root zone should not drop below 50% storage capacity. At peak use, sorghum will use about 80 to 95 mm of water in a 12 day period.

Timing Irrigations

There are a number of ways to determine the proper time to irrigate – soil moisture instruments, taking soil samples, keeping records by logging water use and supply, and by stage of plant growth. Most likely the best system would be a combination of two or more of these, but the most practical method for many growers is to go by stage of plant growth (see Figure 4.2.1.)

When irrigation water is in limited supply, the pre-plant application should be followed by one watering applied just as the sorghum starts to boot.

Should rainfall be favourable to the boot stage, this one watering should be delayed as late as possible so it will carry the crop well into the grain development stage.

Should you have a moderate water supply, enough for a pre-plant application plus two waterings, the first irrigation should be applied a few days prior to boot and the second a few days after flowering has been completed. If significant rainfall occurs prior to booting, application of water may be delayed with good results.

Watering up is an alternative to pre-irrigation, especially under overhead irrigation. This aids in the incorporation of pre-emergent herbicides.

Watering-up with surface irrigation also works as long as the beds sub to the top well, and the paddock doesn't have grass weeds.

Planting depth should not be shallower than 3cm when watering up, as herbicide damage can occur and secondary root growth will be poor as the crown will initiate on the soil surface.

If you have enough water for pre-plant plus three irrigations, your best irrigation schedule would be to apply the first irrigation five to seven days prior to boot, the second at boot, and the third 10 days later or by milk stage. Should you plan to apply four or five irrigations, apply the first seven to nine days prior to boot and one every 10 days thereafter.

Total water required during the maturation stage is small but moisture is essential during this stage to ensure full grain fill and to maintain plant quality. Irrigators sometimes encounter the question of when to stop irrigating grain sorghum so as to permit proper grain fill but leave the soil moisture reservoir depleted to allow room for storing off-season precipitation.

In sorghum, the crop is said to be physiologically mature when the grain reaches the hard dough stage. Experience and research indicate soil moisture availability measurements of 50 to 60% of field capacity are adequate to carry the crop once it has reached physiological maturity. In most cases this is around 30 days after flowering.

Figure 4.2.4 Summary of Irrigation management strategies for irrigated grain sorghum

Limited irrigation available		Full Irrigation	
COOL AREA - MEDIUM TO HIGH RAINFALL		**Irrigation scheduling**	**Established plants**
Irrigation scheduling	**Established plants**	Post emergence (4-6 leaves)	
Vegetation stage (6-8 leaves)		Mid vegetative (8-10 leaves)	
Pre-flowering / Late boot	60-100 000 / ha	Late boot / Pre-flowering	100-150 000 / ha
Early grain fill		Early grain fill	
HOT AREA - LOW TO MEDIUM RAINFALL		Mid grain fill	
Irrigation scheduling	**Established plants**		
Vegetation stage (6-8 leaves)			
Pre-flowering / Late boot	40-70 000 / ha		
Early grain fill			

To assist field crop irrigation scheduling decisions, DAFF Queensland have recently released an on-line irrigation scheduling tool Watersched2. This tool simplifies the scheduling of irrigations across all fields on your farm by estimating crop water use from available weather data. This tool automatically downloads daily weather data from different locations in Queensland and New South Wales and using farm-specific inputs conducts a daily soil water balance and economic analysis to determine when and how much to irrigate.

4.3 Irrigated corn – best practice guide

Bec Raymond
DAFF Queensland

Graham Harris
DAFF Queensland

Key points

- Water required varies from 500 to 800 mm
- A full irrigation strategy or limited water irrigation strategy can be used
- Waterlogging can be as detrimental to corn as insufficient water
- The period from tasselling, through silking and until the end of dough is the most sensitive to water stress.
- The timing of the last irrigation will depend on your soil type, available water and the dent stage of the crop
- Where water is limited the yield target must be reduced and appropriate irrigation strategies used
- Corn has a high demand for nitrogen, phosphorus and potassium
- Choose the most appropriate hybrid maturity for your location, planting time and available water
- Match plant populations to hybrid choice and available water
- Plant when soil temperature is above 12ºC at 9am and rising, and aim to avoid flowering during mid-summer, and frost during seedling and before physiological maturity

Plant Water Use

Corn produces large amounts of dry matter and grain where adequate water is supplied.

For maximum production a medium maturity corn grain crop requires between 500 and 800 mm of water depending on the climate.

The amount of water required to produce a corn crop with maximum yield is not a fixed value as temperature and relative humidity during the growing period, along with wind and soil moisture, all determine the rate of evaporation from the soil and transpiration from the plant (evapotranspiration or ET_C). The DAFF Queensland free on-line tool CropWaterUse can be used to examine the seasonal variability in crop water requirement for fully irrigated corn at your location.

Table 4.3.1 summarises the output from CropWaterUse used to estimate the irrigation needed to grow corn at three locations (Dalby, Goondiwindi and Emerald) for a 1 September sowing date. The analysis assumes that the crop is fully irrigated to target maximum yield. An irrigation application efficiency of 75% and a 75mm irrigation target deficit are assumed. Results show a large variation in seasonal crop water demand, rainfall and irrigation demand between locations and season types.

Figure 4.3.1 shows the daily water use in corn which peaks during silking and tasseling (VT to R1). Nearly 24 percent of the total water demand by the crop occurs in this three week period. From week 5 to week 11 a fully irrigated corn crop will use 71 per cent of its total water requirement.

The area of irrigated corn to plant is a function of corn price, available water and your planned irrigation strategy.

Irrigation Strategies

Full Irrigation

Table 4.3.2 summarises the impact of excessive and inadequate water on corn at different growth stages. Key points to consider for fully-irrigated corn are:

- Evapotranspiration (ET_C) is usually linearly related to crop yield. Stressing the crop at any stage of development reduces ET_C and yield. This yield loss cannot be recovered by irrigating at a later time.
- Corn planted at the optimum time should not need irrigation before the V4 stage. There is usually adequate soil moisture just below the dry soil surface and ETC is usually low at this time due to lower temperatures early in the crop season.

Table 4.3.1 Comparison of average water requirements for corn planted on the 1 September at Goondiwindi, Dalby and Emerald, based on historical weather data (1957 to 2008)

	Goondiwindi			Dalby			Emerald		
Season Type	Dry	Ave	Wet	Dry	Ave	Wet	Dry	Ave	Wet
Crop ET_c (mm)	649	605	594	599	565	548	677	663	623
In-crop Rainfall (mm)	141	216	303	163	268	350	128	202	347
Irrigation Demand (ML/ha)	6.5	5.2	4.5	5.7	4.2	3.7	7.2	6.3	4.7
No. of Irrigations	6	5	4	6	4	4	7	6	5

- As the crop begins more rapid vegetative growth and temperatures increase it is important to keep the plant available water content (PAWC) between 50% (the refill point) and 100% (full point). Remember that waterlogging can be as detrimental to corn as water deficit.

  The period beginning just prior to tasseling (VT) and lasting into the milk stage (R3), especially at or near silk emergence (R1) is the most important period for water supply to the crop.
- Daily water use varies throughout the season depending on weather conditions and stage of growth (see Figure 4.3.1).
- The crops ability to take up water increases as the canopy develops, peaking at the silking stage (R1). Hot, drier conditions will increase the crop's water requirement and taller crops with thicker canopies require more water than shorter crops.

Figure 4.3.1 Average daily water use pattern for corn and critical growth stages

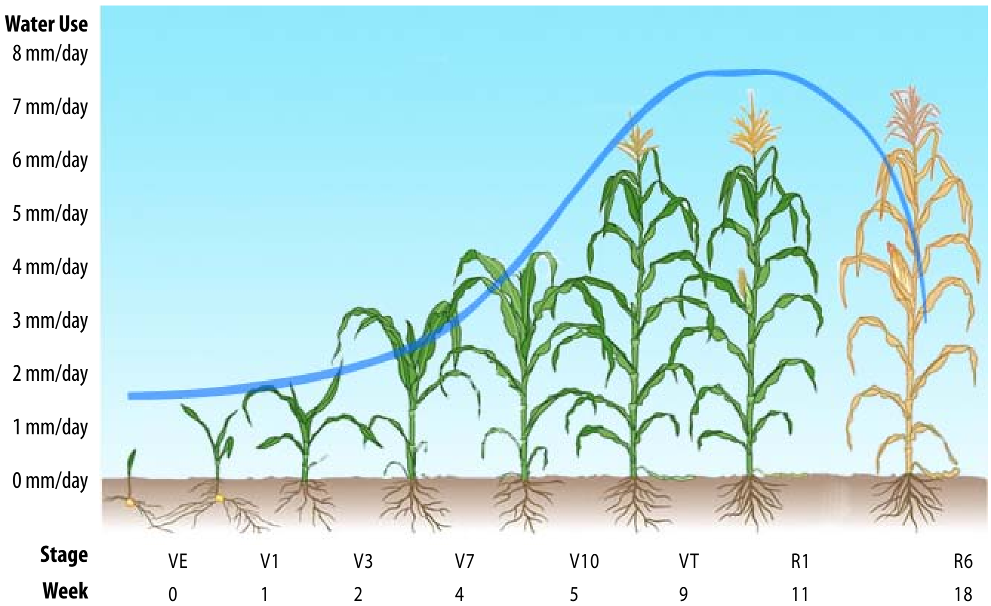


Chart for a 1 September planted crop at Dalby – daily water use values for hotter districts like Emerald would be 10 to 20% higher.

- Yield reductions of up to 50% can occur if the corn is wilted for four days at the end of the pollination period (R0). Even in the dough stage (R4) four consecutive days of wilting can reduce yield by 40%. However, four days of wilting at least a week prior to tasseling (VT) may only result in a 10% yield reduction.
- Water management during the grain filling period is vital. This period for corn is 1/3 longer than for grain sorghum
- The decision to stop irrigation needs to take account of crop stage, soil type and PAWC. There needs to be enough water to fill out the grain while saving water and energy. Corn reaches physiological maturity about 2 weeks after the full dent stage (R5), and the crop normally requires about 60mm of water during this period. Sandy soils require a fully recharged profile to supply this much water and on these soils irrigation should not be stopped until a week after full dent. For heavier textured clays the necessary 60mm can be held in around 30cm of moist soil, and irrigation may be stopped 4 to 5 days after early dent, even before the full dent stage.

Irrigations can be scheduled based on soil moisture monitoring using one of the commercial soil moisture monitoring tools available. This equipment can tell you the rate of crop water use and the depth of water extraction.

This can be used to make irrigation scheduling decisions.

Irrigation can also be scheduled based on estimation of crop ET_c from weather data. Watersched2, a free online irrigation scheduling tool developed by DAFF Queensland is now available. This tool automatically downloads daily weather data from different locations in Queensland and New South Wales and using farm-specific inputs conducts a daily soil water balance and economic analysis to determine when and how much to irrigate.

Figure 4.3.2 is an example of the end of season report generated by WaterSched2 for an irrigated corn crop at Dalby in the 2009-10 season. This report summarises the water, crop and economic data for the crop. It provides the WUE indices for predicted and actual yield achieved. The graph at the bottom of the report shows the daily soil water depletion.

During the season, this report provides the information needed by the grower to decide on their most appropriate irrigation scheduling strategy in response to crop water requirements, likely economic returns and whole farm water availability.

Limited Water Strategies

If there is a high probability of reduced water allocation and insufficient rainfall, then the yield target may need to be revised down, and supplementary irrigation strategies adopted. Supplementary irrigated crops are 'water limited' – there is not enough water available to fully irrigate the area to be sown.

Growers faced with this situation have two main choices:

1. maximise production per hectare by growing an area that can be fully irrigated from the water available
2. grow the largest possible area possible where irrigation is only applied during the most critical growth stages.

Growers wanting to maximise productivity per ML of water will need to strike a balance between these options based on their local conditions and climatic forecasts. Growing a smaller, fully irrigated area of crop may limit the potential upside but avoids the extra costs associated with growing a larger area. On the other hand, yield may be poor if a larger area is planted and seasonal conditions are not favourable.

Where the crop cannot be fully irrigated and a limited water strategy is being implemented it is important to time the first in-crop irrigation prior to tasselling (VT). Follow-up irrigations should be applied during the silking (R1) and blister (R2) stage. If possible, irrigation should be continued through until the end of the dough stage to prevent wilting. Stress late in the season (from dent stage to maturity) has the least impact on yields so irrigation should cease at these stages.

Table 4.3.2 Critical crop management considerations by growth stage for corn

Stage		Week	Description	Crop Management Consideration
Seedling	VE	0	Emergence	If soil is too wet, too cold or too dry, germination will be slow and young seedlings may die before establishment. Shortages of major elements may slow growth and development.
	V1	1	Collar of first leaf visible.	
Vegetative	V2	2	2 leaves fully emerged	All leaves are formed during the first 3 weeks of growth by a single growing point below the ground surface. Wet or dry conditions will slow seedling growth. Plants are susceptible to flooding, especially if temperatures are high.
	V5	3	5 leaves fully emerged	
	V8	4-5	8 leaves fully emerged. Tassel and ear initiation.	Around 30 days after planting the growing point is at the ground surface and, having formed all the leaves, develops into an embryonic tassel.
	V12	6	12 leaves	The plant has a high requirement for nutrients and water. Water stress will restrict leaf cell growth resulting in smaller leaves, a shorter plant and less yield potential. The plant undergoes rapid vertical growth and the roots rapidly fill most of the root zone. Cob size is determined over this period – the number of rows per ear first, then kernels per row.
	V16	7	16 Leaves	
	Vn	8	n leaves	
Flowering and Fertilization	VT	9	Last branch of tassel completely visible	The corn plant directs most of its energy and nutrient towards producing kernels on an ear. There is a heavy demand for water and nutrients. Severe moisture stress will give poor pollination and reduce kernel development. Stress in the early part of the period will affect kernel numbers while stress in the latter part will affect kernel weight. A poor seed set is usually the result of nutrient or water shortages that either delay silking or result in kernels aborting after pollination.
	R0	10	Athesis or male flowering. Pollen shed begins.	
	R1	11	Silks are visible.	
Grain filling and Maturity	R2	12 -18	Blister stage. Kernels are filled with clear fluid and the embryo can be seen.	This stage chiefly determines kernel size – moisture stress will hasten maturity and reduce kernel fill through reduced photosynthesis and starch production, resulting in lower yields. Similarly, very favourable conditions of moisture and fertility will result in improved kernel fill and a better yield than expected. The last irrigation is important for final kernel size and is especially important for grit corn production. At 50 to 70 days after pollination the corn kernel will have reached its greatest dry weight and it is physiologically mature – there will be no further response to additional water.
	R3		Milk stage. Kernels are filled with white, milky fluid.	
	R4		Dough stage. Kernels filled with white paste.	
	R5		Dent stage – milk line is close to the base of grain.	
	R6		Physiological maturity.	The appearance of a 'black' layer at the base of the grain indicates physiological maturity

Figure 4.3.2 WaterSched2 End of Season Field Summary report for a fully irrigated wheat crop at Dalby in 2009

WaterSched2

Report Compiled By:
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End of Season Summary

Field Summary

Farm:	Wallon Park	**Plant Date:**	1/09/2009
Location:	Dalby	**Season:**	2009/2010
Field Name:	Wallon Park	**Length of Season:**	147 days / 2093 GDD
Field Size:	100 ha	**Irrigation Type:**	Surface 100%
Crop:	Late Maize	**Irrigation Trigger Deficit:**	75 mm

Water Summary

	mm	ML/ha
Total Irrigation:	400	4
Total Rainfall:	149	1.49
Total Losses:	100	1
Starting Soil Water:	178	1.78
Ending Soil Water:	30	0.3
Soil Water Change:	148	1.48
Total Water Input:	697	6.97
Net Water Supply:	597	5.97

Crop Summary

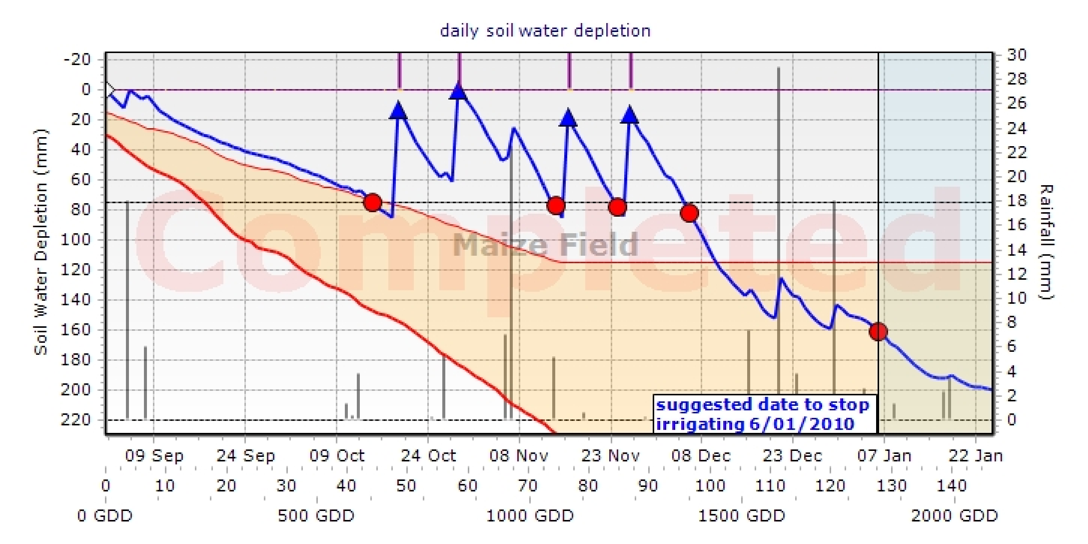
Expected Yield:	12 tonnes/ha
Predicted Yield:	10.6 tonnes/ha
Actual Yield:	10 tonnes/ha
Accumulated ETp:	657 mm
Accumulated ETc:	597 mm

Economics Summary

Price Per Unit:	$250 / tonnes
Variable Costs:	$1310 / ha
Gross Margin:	$1190 / ha

Water Use Efficiency

	Predicted	Actual	Gross Margin
Total Water Use Index TWUI	1.53 tonnes / ML	1.43 tonnes / ML	$170 / ML
Gross Production Water Use Index GPWUI	1.78 tonnes / ML	1.68 tonnes / ML	$200 / ML
Irrigation Water Use Index IWUI	2.66 tonnes / ML	2.5 tonnes / ML	$298 / ML
Crop Water Use Index CWUI	17.81 kg / mm	16.75 kg / mm	$1.99 / mm



Friday, 16 November 2012 *End of Season Field Summary* **Page 1 of 1**

Agronomy

To achieve high irrigated yields it is necessary to follow good agronomic practices. High yielding crops use water more efficiently than lower yielding crops.

Nutrition

Soil test regularly so that the most appropriate nutrition program can be drawn up based on your yield expectations.

The three major nutrients required by corn are nitrogen (N), phosphorus (P) and potassium (K). At least 340 kg N/ha is needed to grow a 12.5 t/ha corn crop. This crop would also require 55 kg P/ha, 245 kg K/ha and 38 kg sulphur/ha.

The corn plant rapidly takes up N, P and K beyond the 4 to 5 week (V8) period. Nitrogen is usually applied in a split application with 60-70% applied pre-plant and the remainder either water run or side dressed prior to tasseling (VT). Phosphorus and potassium are usually applied pre-planting or at planting as starter fertiliser.

Variety Choice

Corn hybrids are rated by maturity by comparing the moisture at harvest with a standard hybrid. This is called the Comparative Relative Maturity (CRM) and is commonly referred to as the days from planting to physiological maturity (black layer or R6). The actual days to maturity vary greatly with location, planting time and other environmental factors. The CRM maturity for Australian locations are summarised in Table 4.3.3.

Generally speaking, a longer maturity hybrid has a higher yield potential than a quick maturity hybrid (under ideal conditions). Advances in plant breeding have lessened this difference.

There are many factors to consider in choosing a particular maturity hybrid. Quicker maturity hybrids may be chosen in response to:

- limited water availability or the desire to finish the crop before peak water requirements for other crops in January-February.
- Delayed spring planting with the aim of beating the summer heat before tasselling
- A late plant may be considered and there is a threat of an early frost

Choose a range of hybrids that perform well in both favourable and less favourable conditions.

Table 4.3.3 Guide to corn maturity plantings

Location	CRM Maturity (days)
MIA, Lachlan and Macquarie Valleys	105 - 118
Liverpool Plains and Northern NSW	108 – 118
Darling Downs and Burnett	108 – 120
Central Queensland and Burnett	111 – 118
North Queensland	118 - 130

Row spacing

For irrigated crops, rows of 76cm to 100cm are used, with most planters set up for 90cm rows.

Under fully irrigated conditions the narrower rows have a slight yield advantage.

Plant population

Plant population is a critical decision in response to the hybrid chosen, water availability and planting time. Higher plant populations deplete available soil water at a faster rate than lower populations and irrigation frequency needs to increase accordingly. Higher populations also speed up maturity by up to 7 days.

Planting Date

Choice of planting date should be based on:

- Avoiding flowering during the expected peak temperature periods and working back to a suitable planting date for your hybrid of choice
- Plant when the soil temperature is at least 12ºC at 9am at a depth of 10cm for 3 to 4 consecutive days and is rising
- Avoiding seedling frosts on Spring planted corn that will damage the growing point or early frosts on late planted corn before physiological maturity (black layer)

Further Reading

Pacific Seeds - Cropping Yearbook

Pioneer - Growth Potential: Corn growers' Workshop

4.4 Irrigated Chickpeas – Best Practice Guide

Gina Mace
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Key points

- Water required varies from 350 to 500 mm
- Chickpeas are particularly sensitive to waterlogging, particularly if irrigated when the soil has been allowed to crack open
- Planting into pre-irrigated fields can lead to poor crop establishment. Planting dry and watering up may be preferred to establish the crop.
- Field selection and fast watering practices are needed to minimise the risk of crop death through waterlogging.
- Scheduling irrigations when PAWC is at 40% depletion rather than using crop growth stage as the trigger minimises crop loss from waterlogging.
- Crops are most sensitive to waterlogging at full flower and late pod-fill.
- Attention to varietal choice, planting date, row spacing, and plant population are critical to achieving a profitable chickpea crop
- Implement an Integrated Disease Management program to manage serious disease risks – Phytophthora root rot, Ascochyta blight and Botrytis Grey Mould

Plant Water Use

A chickpea crop achieving maximum production will use between 350 and 500 mm of water depending on seasonal conditions.

The amount of water required to produce a chickpea is not a fixed value as temperature and relative humidity during the growing period, along with wind and soil moisture, all determine the rate of evaporation from the soil and transpiration from the plant (evapotranspiration or ET_c). The DAFF Queensland free on-line tool CropWaterUse can be used to examine the seasonal variability in crop water requirement for irrigated chickpea at your location.

Table 1 summarises the output from CropWaterUse used to estimate the irrigation needed to grow chickpeas at three locations Emerald (15 May planting date), Dalby and Narrabri (1 June planting date). The analysis assumes that the crop is fully-irrigated to target maximum yield. A 75% irrigation application efficiency and a 75mm irrigation trigger deficit are assumed. Results show a large variation in seasonal crop water demand, rainfall and irrigation demand between locations and season types.

Figure 4.4.1 shows the daily water use in chickpea which peaks during podding and seed development (R6 to R9).

The area of irrigated chickpea to plant is a function of chickpea price, available water and your planned irrigation strategy.

Irrigation Strategies

Full Irrigation

Table 4.4.2 summarises the impact of excessive and inadequate water on chickpea at different growth stages. Chickpeas are generally not fully irrigated because of the impact of even short term waterlogging on crop performance. This risk also interacts with soil type – the negative impact of waterlogging increases with increases in clay content. The losses are greatest on heavy black earths (with 70 to 80% clay) and least on medium grey clays (40 to 50% clay).

As the crop is more sensitive to waterlogging than winter cereals a different irrigation scheduling strategy is needed. This strategy also varies with the irrigation system used.

For furrow irrigation the key strategies are:

- Select fields with good layout and tail water drainage, enabling fast irrigation events (preferably less than 8 hours in duration)
- Use high volume beds or hills, with relatively good grades (avoid flat grades)

Table 4.4.1 Comparison of average water requirements for chickpeas planted on the 15 May at Emerald, and the 1 June at Dalby and Narrabri based on historical weather data (1957 to 2008)

	Narrabri			Dalby			Emerald		
Season Type	Dry	Ave	Wet	Dry	Ave	Wet	Dry	Ave	Wet
Crop ET_c (mm)	424	396	364	449	419	398	413	393	366
In-crop Rainfall (mm)	130	221	367	114	188	279	36	93	199
Irrigation Demand (ML/ha)	4.0	2.8	1.7	4.3	3.5	2.7	4.6	3.9	2.9
No. of Irrigations	4	3	2	4	3	3	4	4	3

- Pre-irrigation to fill the profile can lead to poor crop establishment due to soil smearing and crack formation along the planting line.
- Watering up is used to successfully establish the crop in the optimum planting window. It does however run the risk of germinating a first flush of weeds along with the crop.
- Do not allow the soil to dry out and form deep cracks. This cracking damages roots, providing an opportunity for soil borne diseases to infect during the irrigation event and causing additional stress on the crop.
- On lower clay content soils, irrigate early, before soil cracking, and use more frequent irrigations.

On higher clay content soils a quick watering prior to flowering (R1) to top up the profile, if needed, is recommended.

- Irrigation is not recommended once flowering has commenced.
- Avoid saline or sodic soils as chickpeas are extremely sensitive to salinity and unable to access water and nutrients from saline layers in the soil. Saline and sodic layers in the top 90cm of soil will severely limit root development and water extraction.
- Optimise furrow irrigation by watering every second furrow and doubling-up siphons where necessary
- Do not irrigate if there is a likelihood of rain immediately following the irrigation event.

Figure 4.3.1 Average daily water use pattern for chickpea and critical growth stages

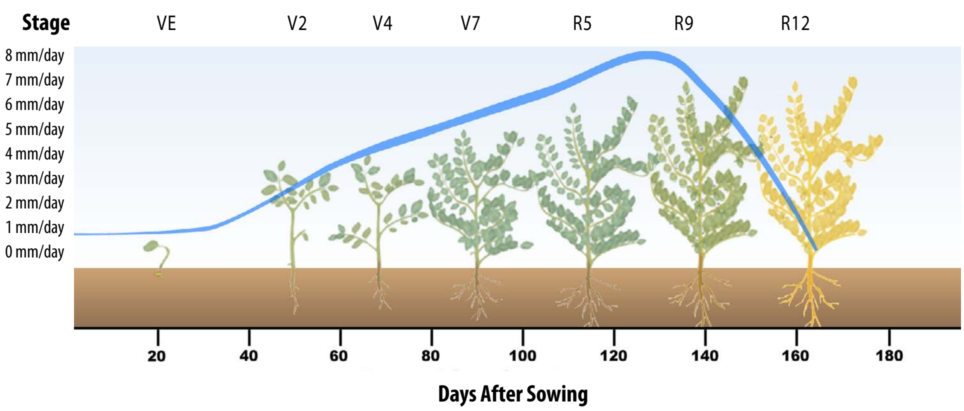

Chart for a 1 June planted crop at Dalby – daily water use values for hotter districts like Emerald would be 10 to 20% higher.

For sprinkler irrigation the risk of water logging is less significant as the amount and time of water application is better controlled. However, the risk of foliar fungal diseases such as ascochyta blight and botrytis grey mould is increased. It is important to apply recommended fungicides before irrigating with overhead sprinklers. LEPA systems may provide similar flexibility in timing and amount of water application without increased disease risk.

Daily water use varies throughout the season depending on weather conditions and stage of growth (see Figure 4.4.1). The crops ability to take up water increases as the canopy develops, peaking during the seed fill period (R8 and R9) – this coincides with warmer spring temperatures.

Irrigations can be scheduled based on soil moisture monitoring using one of the commercial soil moisture monitoring tools available. This equipment can tell you the rate of crop water use and the depth of water extraction.

This can be used to make irrigation scheduling decisions (bearing in mind the importance of minimising waterlogging with this crop and foliar disease implications).

Irrigation can also be scheduled based on estimation of crop ET_c from weather data. Watersched2, a free online irrigation scheduling tool developed by DAFF Queensland is now available. This tool automatically downloads daily weather data from different locations in Queensland and New South Wales and, using farm-specific inputs, conducts a daily soil water balance and economic analysis to determine when and how much to irrigate.

Figure 4.4.2 is an example of the end of season report generated by Watersched2 for an irrigated chickpea crop at Dalby in the 2009 season. This report summarises the water, crop and economic data for the crop. It provides the WUE indices for predicted and actual yield achieved. The graph at the bottom of the report shows the daily soil water depletion.

During the season this report provides the information needed to decide on the most appropriate irrigation scheduling strategy in response to crop water requirements, likely economic returns and whole farm water availability.

Limited Water Strategies

If there is a high probability of reduced water allocation and insufficient rainfall, then the yield target may need to be revised down, and supplementary irrigation strategies adopted. Supplementary irrigated crops are 'water limited' – there is not enough water available to fully irrigate the area to be sown. Growers faced with this situation have two main choices:

1. maximise production per hectare by growing an area that can be fully irrigated from the water available
2. grow the largest possible area possible where irrigation is only applied during the most critical growth stages.

Growers wanting to maximise productivity per ML of water will need to strike a balance between these options based on their local conditions and climatic forecasts. Growing a smaller, fully irrigated area of crop may limit the potential upside but avoids the extra costs associated with growing a larger area. On the other hand, yield may be poor if a larger area is planted and seasonal conditions are not favourable.

With chickpeas, the first option is preferred given its susceptibility to waterlogging under moisture stress. Ideally chickpeas should be irrigated when the deficit is 30 to 40% of PAWC in the root zone (before significant soil cracking is observed).

If the second option is to be implemented it is best to pre-irrigate a larger area and grow the crop as raingrown.

Table 4.4.2 Critical water management considerations by growth stage for chickpea

Stage	Stage Length (Days)[1]	Description	Water Management Consideration
VG	7 to 15	**Germination**	Adequate soil moisture essential to establish desired plant population. Soil smearing and subsequent crack formation reduce establishment if planted with disc-openers in too wet a seedbed.
VE	40 to 80	**Emergence – seedling** emerges	
V1		**First Node** – 1st multifoliate leaf at first node fully unfolded	Do not allow the soil to dry below 50% of plant available water content (PAWC). Beyond this the soil will crack open, damaging the root system and leading to plant death if irrigated at this time. Better to apply irrigation with depletion at around 40% PAWC to prevent soil cracking. Do not irrigate before rainfall events and use best management irrigation practices. Apply fungicides before irrigating with sprinkler irrigation.
V2		**Second Node** – 1st multifoliate leaf at second node fully unfolded	
V3		**Third node** - – 1st multifoliate leaf at third node fully unfolded	
V(n)		**nth node** – 1st multifoliate leaf at nth node fully unfolded	
R1	20 to 30	**Start flowering** – one flower bud at any node on the main stem	Continue to irrigate at around 40% depletion of PAWC rather than using plant growth stage as an irrigation trigger. Do not irrigate when the crop is fully flowering and soil cracks are present as crop death will result.
R2		**Calyx opening** – bud grows but is still sterile, sepals begin to form	
R3		**Anthesis** – pollination occurs before bud opens	
R4		**Wings extend** – flower petals extend to form flower	
R5		**Flower Collapses**	
R6	10 to 15	**Pod initiation** – one pod found in any nod on the main stem	Continue to irrigate at around 40% depletion of PAWC rather than using plant growth stage as an irrigation trigger. Do not irrigate in late pod fill – chickpeas are especially sensitive to waterlogging at this time.
R7		**Full pod** – one fully expanded pod present	
R8	10 to 15	**Beginning seed** – one fully expanded pod in which seed cotyledon growth is visible	Irrigate when soil water depletion is around 30 to 40% of PAWC – this is more important than basing irrigation on crop growth stage.
R9		**Full seed** – one pod on the main stem filled by seeds when fresh	
R10	20 to 30	**Beginning maturity** – one pod on the main stem turns to a light golden yellow colour	Irrigation should not be required beyond this stage.
R11		**50% of pods golden yellow**	
R12		**90% of pods golden yellow**	

Figure 4.4.2 WaterSched2 End of Season Field Summary report for an irrigated chickpea crop at Dalby in the 2009 season

WaterSched2

Report Compiled By:
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End of Season Summary

Field Summary

Farm:	Wallon Park	**Plant Date:**	1/06/2009
Location:	Dalby	**Season:**	2009
Field Name:	Wallon Park	**Length of Season:**	157 days / 2415 GDD
Field Size:	100 ha	**Irrigation Type:**	Surface 100%
Crop:	Early Chickpea	**Irrigation Trigger Deficit:**	75 mm

Water Summary

	mm	ML/ha
Total Irrigation:	200	2
Total Rainfall:	74	0.74
Total Losses:	50	0.5
Starting Soil Water:	230	2.3
Ending Soil Water:	33	0.33
Soil Water Change:	197	1.97
Total Water Input:	471	4.71
Net Water Supply:	421	4.21

Crop Summary

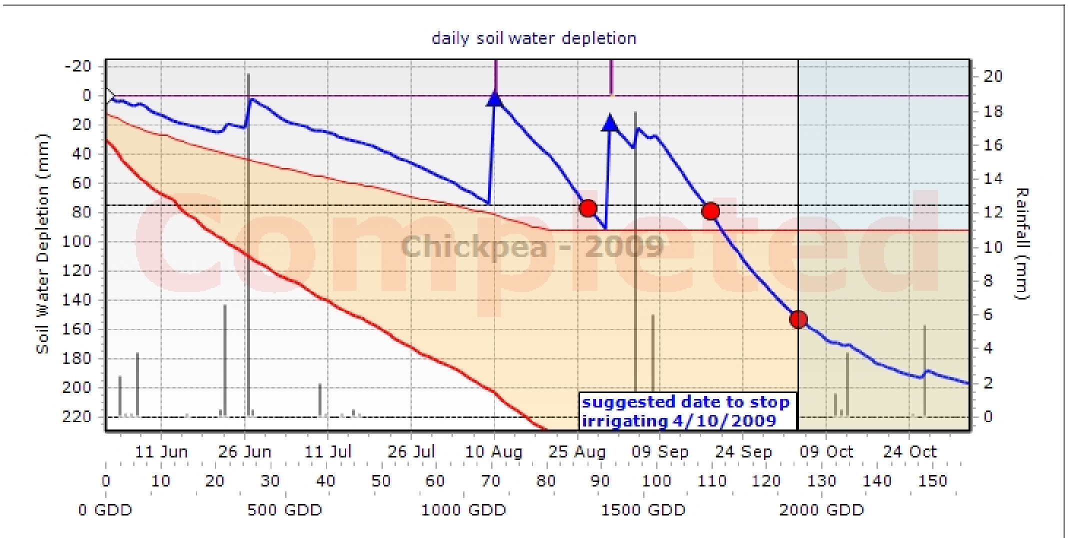
Expected Yield:	4 tonnes/ha
Predicted Yield:	3.1 tonnes/ha
Actual Yield:	2.5 tonnes/ha
Accumulated ETp:	508 mm
Accumulated ETc:	421 mm

Economics Summary

Price Per Unit:	$440 / tonnes
Variable Costs:	$605 / ha
Gross Margin:	$495 / ha

Water Use Efficiency

	Predicted	Actual	Gross Margin
Total Water Use Index TWUI	0.67 tonnes / ML	0.53 tonnes / ML	$105 / ML
Gross Production Water Use Index GPWUI	0.75 tonnes / ML	0.59 tonnes / ML	$117 / ML
Irrigation Water Use Index IWUI	1.57 tonnes / ML	1.25 tonnes / ML	$248 / ML
Crop Water Use Index CWUI	7.46 kg / mm	5.94 kg / mm	$1.18 / mm



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Agronomy

To achieve high irrigated yields it is necessary to follow good agronomic practices. High yielding crops use water more efficiently than lower yielding crops.

Variety Choice

Choice of variety is based on yield potential and adaptation for specific locations, disease resistance, maturity, plant height and lodging potential, and suitability for target market.

For irrigated chickpeas choose varieties with the highest possible Phytophthora root rot resistance. This is critical on soils with the highest clay contents.

Choose a variety with the highest possible Ascochyta blight resistance. This is very important where sprinkler irrigation is applied.

There is also some variation in the level of salt tolerance amongst chickpea varieties. They should not be planted where the soil chloride is in excess of 800 mg/kg within the top 60 cm of the root zone. If salt is a risk choose varieties with the highest salt tolerance.

Planting Date

If the average daily temperature falls below 15ºC chickpea flowers will abort.

Choice of sowing date is a trade-off between sowing early with high yield potential in years with a warmer spring versus lower yield potentials with delayed sowing to ensure flowering occurs in temperatures closer to 15ºC in cooler springs.

If sown too early the crop will grow vegetatively and use soil water, reducing water productivity. Choose the most appropriate sowing window for your variety and location.

Row spacing

Row spacings of 18 cm to 100 cm are used. The choice is largely determined by available planting equipment, the existing field layout and tillage practices (whether zero-tilled or cultivated).

Where the yield potential is less than 1.5 t/ha, row spacings out to 100 cm have little impact on yield potential. However, where the yield potential is above 1.5 t/ha the wider row spacings give a yield reduction of 10 to 15% and increase the risk of lodging.

Plant population

Yields are generally stable within the range of 20 to 40 plants per square metre.

A target of 25 to 30 plants per square metre should be used. Where wide row spacings are used (100 cm) a population of 20 plants per square metre should be used – in this situation a higher plant population result in thin main stems and increased lodging risk.

The higher populations should be used where planting late in the planting window.

Disease Management

Disease management is critical in chickpea. In irrigated situations Phytophthora root rot can be particularly devastating. Paddock and varietal selection are critical to managing this disease. Only use varieties with the highest possible resistance, and select paddocks which are well drained, can be watered quickly and ideally have not grown chickpeas for at least two years.

Ascochyta blight and Botrytis grey mould are also very significant diseases in chickpeas. Use seed treated with fungicides for these diseases. For Ascochyta, spray with a registered fungicide before the first post-emergent rain event (or sprinkler irrigation) and again before the second post-emergent rain event (or sprinkler irrigation).

Botrytis grey mould (BGM) is particularly severe during wet spring conditions, when a combination of canopy closure, frequent rainfall (or sprinkler irrigation events) and overcast conditions results in prolonged periods of plant wetness. In conditions favouring the disease a preventative spray of a registered fungicide immediately prior to canopy closure, followed by a second application two weeks later will assist in minimising BGM development.

For more detail on disease management refer to the Northern Pulse Bulletins in the further reading section.

Further Reading

Cumming, G. 2011 Certified Chickpea Agronomy Course 2011, Pulse Australia

Moore et al 2011 Chickpea: Ascochyta Blight Management, Northern Pulse Bulletin, Pulse Australia

Moore et al 2011 Chickpea: Phytophthora Root Rot Management, Northern Pulse Bulletin, Pulse Australia

Ryley et al 2011 Chickpea: Integrated Disease Management, Northern Pulse Bulletin, Pulse Australia

Ryley et al 2011 Chickpea: Botrytis Grey Mould Management, Northern Pulse Bulletin, Pulse Australia

Slatter, J. and Lucy, M. 2002 Fine-tuning irrigation management of chickpeas, Australian Cottongrower, 23(3): 42-43

4.5 Irrigated soybeans – best practice guide

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Key points

- Water required varies from 600 to 800 mm
- A full irrigation strategy is preferred as soybeans are very sensitive to moisture stress
- Plant into a full profile (pre-irrigation may be required) and avoid watering up.
- The first irrigation is unnecessary before the V4 stage (four sets of trifoliate leaves unfolded). Stress beyond this stage will shorten plants and produce low set pods.
- Excessive, frequent irrigations will produce tall plants prone to lodging and Sclerotinia.
- Flowering (R1 and R2) and podding (R3 and R4) are the most sensitive stages to water stress.
- During early podfill (R5) moisture levels should be maintained above 50% of available water to minimise pod abortion. Moisture stress later in podfill (R6) reduces seed size.
- The last irrigation must be timed so beans will reach maximum weight – this occurs after the first leaf yellowing.
- Attention to varietal choice, planting date, row spacing, plant population and nutrition are critical to achieving a profitable soybean crop

Plant Water Use

A soybean crop achieving maximum production will use between 600 and 800 mm of water depending on the weather.

The amount of water required to produce a soybean is not a fixed value as temperature and relative humidity during the growing period, along with wind and soil moisture, all determine the rate of evaporation from the soil and transpiration from the plant (evapotranspiration or ET_C). The DAFF Queensland free on-line tool CropWaterUse) can be used to examine the seasonal variability in crop water requirement for fully irrigated soybean at your location.

Table 4.5.1 summarises the output from CropWaterUse used to estimate the irrigation needed to grow soybean at three locations (Dalby, Goondiwindi and Emerald) for a 1 December sowing date. The analysis assumes that the crop is fully-irrigated to target maximum yield. An irrigation application efficiency of 75% and a 75 mm irrigation target deficit are assumed. Results show a large variation in seasonal crop water demand, rainfall and irrigation demand between locations and season types.

Figure 4.5.1 shows the daily water use in soybean which peaks during podding and seed fill (R3 to R5).

The area of irrigated soybean to plant is a function of soybean price, available water and your planned irrigation strategy.

Irrigation Strategies

Full Irrigation

Table 4.5.2 summarises the impact of excessive and inadequate water on soybean at different growth stages. Key points to consider for fully irrigated soybean are:

- Actively growing soybeans can water from depths of 90 to 120 cm. To achieve this, a full profile of moisture is needed at planting. **Pre-irrigating** fields one to three weeks prior to planting is recommended and plant into moisture as soon as the soil is dry enough to work
- **Watering up** to establish soybeans planted into dry soil only works with furrow irrigation on uniform, self-mulching clays. Seed must be covered with soil and the seed line must remain above the furrow water level. Watering up is not suited to soils prone to hard setting or crusting, and is not recommended in fields that have not previously grown soybean, as the hot dry conditions can kill rhizobia reducing nodulation effectiveness. Very hot conditions can also kill emerging seedlings.

Table 4.5.1. Comparison of average water requirements for soybeans planted on the 1 December at Goondiwindi, Dalby and Emerald, based on historical weather data (1957 to 2008)

	Narrabri			Dalby			Emerald		
Season Type	Dry	Ave	Wet	Dry	Ave	Wet	Dry	Ave	Wet
Crop ET_c (mm)	759	726	691	671	633	622	697	657	614
In-crop Rainfall (mm)	175	274	445	208	312	462	212	337	505
Irrigation Demand (ML/ha)	8.0	6.7	5.5	6.1	4.9	4.6	6.7	5.5	4.3
No. of Irrigations	8	6	5	6	5	4	6	5	4

- Ideally soybeans should be planted into a full profile at the optimum time. A crop established this way should not need irrigation before the V4 stage, usually around 40 days after planting. Moisture stress beyond this period will shorten internode length and overall plant height. This can result in low pod height that can exacerbate harvest difficulties.
- On the other hand, frequent light irrigations (less than 25mm) during the vegetative stages will increase crop height that can induce lodging and losses from diseases such as Sclerotinia. They will also produce a shallow rooted crop.

As the crop begins more rapid vegetative growth water use increases until around 70% groundcover. Plant available water content (PAWC) should be kept above 50% (the refill point).

- Flowering (R1 and R2) and podding (R3 and R4) are the most sensitive stages to water stress. Late flowering and early podding stress reduces pod number and yield potential.
- During early podfill (R5) moisture levels should be maintained above 50% of available water to minimise pod abortion. Moisture stress later in podfill (R6) reduces seed size.

Figure 4.5.1. Average daily water use pattern and critical growth stages for soybean

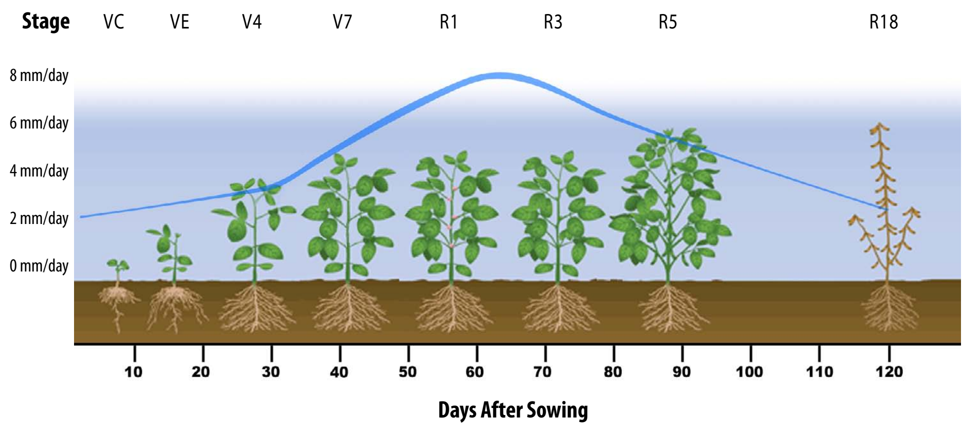

Chart for a 1 December planted crop at Dalby – daily water use values for hotter districts like Emerald would be 10 to 20% higher.

- Soybeans continue to extract soil water until all seed is physiologically mature. This means that the crop will continue using water beyond the first leaf yellowing. Water deficit beyond this will result in shrivelled seed and poor seed quality.
- Daily water use varies through out the season depending on weather conditions and stage of growth (see Figure 4.5.1). The crops ability to take up water increases as the canopy develops, peaking at the late flowering (R2) and early podding (R3) stages. Hot, drier conditions will increase the crop's water requirement.
- The final irrigation must be applied late enough to ensure moisture is available until the beans have gained maximum weight (Stage R8). This occurs at the R6 stage when the beans within the pods are touching. Inspect several pods at about four nodes down from the terminal of the plant to determine this stage. On heavier soil types this usually means that the last irrigation should be applied when the first yellow leaves appear in the crop – 15 to 20% of pods should be brown. On lighter soils with lower plant available water content, apply the final irrigation when 30% of the pods are brown.

Irrigations can be scheduled based on soil moisture monitoring using one of the commercial soil moisture monitoring tools available. This equipment can tell you the rate of crop water use and the depth of water extraction. This can be used to make irrigation scheduling decisions.

Irrigation can also be scheduled based on estimation of crop ET_c from weather data. Watersched2, a free online irrigation scheduling tool developed by DAFF Queensland is now available. This tool automatically downloads daily weather data from different locations in Queensland and New South Wales and, using farm-specific inputs, conducts a daily soil water balance and economic analysis to determine when and how much to irrigate.

Figure 4.5.2 is an example of the end of season report generated by Watersched2 for an irrigated soybean crop at Dalby in the 2009-10 season. This report summarises the water, crop and economic data for the crop. It provides the WUE indices for predicted and actual yield achieved. The graph at the bottom of the report shows the daily soil water depletion.

During the season, this report provides the information needed to decide on the most appropriate irrigation scheduling strategy in response to crop water requirements, likely economic returns and whole farm water availability.

Limited Water Strategies

If there is a high probability of reduced water allocation and insufficient rainfall, then the yield target may need to be revised down, and supplementary irrigation strategies adopted. Supplementary irrigated crops are 'water limited' – there is not enough water available to fully irrigate the area to be sown. Growers faced with this situation have two main choices:

1. maximise production per hectare by growing an area that can be fully irrigated from the water available
2. grow the largest possible area possible where irrigation is only applied during the most critical growth stages.

Growers wanting to maximise productivity per ML of water will need to strike a balance between these options based on their local conditions and climatic forecasts. Growing a smaller, fully irrigated area of crop may limit the potential upside but avoids the extra costs associated with growing a larger area. On the other hand, yield may be poor if a larger area is planted and seasonal conditions are not favourable.

Under conditions of limited water availability, restricting irrigation during the vegetative stage has the least impact on crop yield. The periods most affected by limited water availability are the later part of flowering (R2) and early pod development (R3). Light water deficits during early flowering can be compensated for by better retention of late flowers and pod set.

When drought stress is severe but is alleviated by irrigation during the reproductive period, yield increase comes primarily from an increase in seed number rather than seed size. Soil moisture levels during pod fill must be kept above 50% of available water to maximise yield.

Table 4.5.2. Critical water management considerations by growth stage for soybean

Stage	Stage Length (Days)[1]	Description	Water Management Consideration
VE	5	**Emergence** – cotyledons above soil surface	Adequate water (between 15 and 50 percent soil water depletion) must be available for germination.
VC	5	**Cotyledon** - Unrolled unifoliate leaves	Water deficiency or excess during the vegetative period will retard growth. Ideally there should be a full profile of moisture at planting. This will reduce the need for frequent irrigation during the vegetative period and encourage plants to develop a good root system – fully irrigated soybeans will extract water to a depth of 90cm. Excessive moisture stress will shorten the internode length resulting in stunted plants. Too frequent irrigation will increase plant height and exacerbate lodging. Irrigation should be managed to ensure the plant height is sufficient for harvest (that the lowest pods are easily harvested), but not great enough to contribute to lodging.
V1	5	**First trifoliate** - One set of unfolded trifoliate leaves	
V2	5	**Second trifoliate** - two sets of unfolded trifoliate leaves	
V4	5	**Fourth trifoliate** - four sets of unfolded trifoliate leaves	
V(n)	3	**nth trifoliate** – V stages continue with the unfolding of trifoliate leaves	
R1	3	**Beginning of flowering** – plants have at least one flower on any node	Flowering is much more sensitive to water deficits than the vegetative period. The tolerance to deficits in early flowering is the result of the 4-week flowering period. Light water deficits during this period can be compensated for by better retention of later-formed flowers and pod set. Water stress in late flowering reduces the number of flowers and pod set.
R2	10	**Full flowering** – there is an open flower on one of the upper two nodes	
R3	9	**Beginning pod** – pods are 5mm at one of the four uppermost nodes	Early pod fill is particularly sensitive to water deficits. Stress at this time results in pod drop and loss in yield potential. This can lead to delayed crop maturity as there may be insufficient pods and seed demand to extract existing photosynthate from the plant.
R4	9	**Full pod** – pods are 20mm at one of the four uppermost nodes	
R5	15	**Beginning seed** – seed is 3mm long in the pod at one of the four top nodes on the main stem	Developing soybean seeds place a heavy nutrient demand on the plant. Water stress at this time reduces seed size or causes pod drop. Soil moisture levels should be kept above 50 percent of available water in the root zone until physiological maturity.
R6	18	**Full seed** – pod containing a green seed that fills the pod capacity at one of the four top main stem nodes	
R7	7	**Beginning maturity** – one normal pod on the main stem has reached it's mature pod colour	Soybeans will continue to use soil water following the first sign of leaf yellowing so there needs to be sufficient water available to maintain seed size and yield. Physiological maturity (maximum dry seed weight) occurs when the seed has separated from the pod, commonly when the plant has half defoliated with age.
R8		**Full maturity** – 95% of the pods have reached their full mature colour	

Figure 4.5.2. WaterSched2 End of Season Field Summary report for an irrigated soybean crop at Dalby in the 2009 season

WaterSched2

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End of Season Summary

Field Summary

Farm:	Wallon Park	**Plant Date:**	1/12/2010
Location:	Dalby	**Season:**	2010/2011
Field Name:	Wallon Park	**Length of Season:**	116 days / 1531 GDD
Field Size:	100 ha	**Irrigation Type:**	Surface 100%
Crop:	Medium Soybean	**Irrigation Trigger Deficit:**	75 mm

Water Summary

	mm	ML/ha
Total Irrigation:	300	3
Total Rainfall:	720	7.2
Total Losses:	410	4.1
Starting Soil Water:	178	1.78
Ending Soil Water:	210	2.1
Soil Water Change:	-32	-0.32
Total Water Input:	988	9.88
Net Water Supply:	578	5.78

Crop Summary

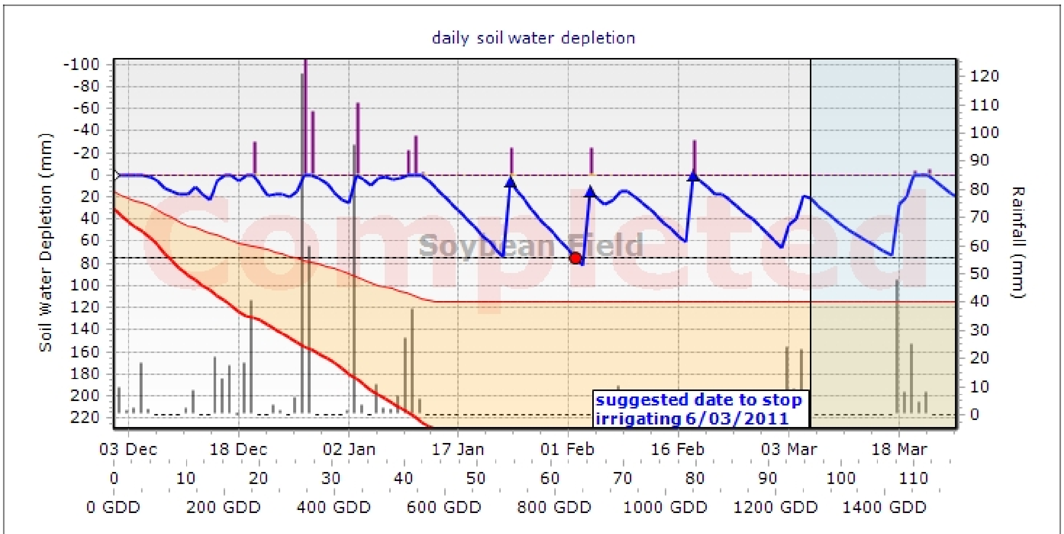
Expected Yield:	4 tonnes/ha
Predicted Yield:	4 tonnes/ha
Actual Yield:	3.75 tonnes/ha
Accumulated ETp:	579 mm
Accumulated ETc:	579 mm

Economics Summary

Price Per Unit:	$500 / tonnes
Variable Costs:	$602.5 / ha
Gross Margin:	$1272.5 / ha

Water Use Efficiency

	Predicted	Actual	Gross Margin
Total Water Use Index TWUI	0.4 tonnes / ML	0.38 tonnes / ML	$129 / ML
Gross Production Water Use Index GPWUI	0.69 tonnes / ML	0.65 tonnes / ML	$221 / ML
Irrigation Water Use Index IWUI	1.33 tonnes / ML	1.25 tonnes / ML	$424 / ML
Crop Water Use Index CWUI	6.91 kg / mm	6.48 kg / mm	$2.2 / mm



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Agronomy

To achieve high irrigated yields it is necessary to follow good agronomic practices. High yielding crops use water more efficiently than lower yielding crops.

Nutrition

Soil test regularly so that the most appropriate nutrition program can be drawn up based on your yield expectations.

The major nutrients required by soybean are nitrogen (N), phosphorus (P), potassium (K), sulphur (S) and zinc (Zn). Soybeans do not need additional nitrogen if the seed is effectively inoculated at planting with Group H rhizobia.

Soybeans use a significant amount of phosphorus which must be available throughout the growing season. The greatest demand starts just before pods begin to form (R3). The crop is generally more responsive to residual phosphorus than that applied to the current crop. Aim to maintain phosphorus levels above 25 mg/kg bicarbonate P. They are also moderately dependent on VAM (vesicular-arbuscular mycorrhizae) which assist uptake of soil phosphorus. Where VAM numbers may be low (following long-fallows) higher rates of phosphorus fertiliser may be necessary.

Potassium is readily taken up by soybeans, with 20 kg of K per tonne of soybeans exported from the field at harvest. Large amounts of potassium will be accumulated in plant material (100 to 150 kg K/ha).

Variety Choice

Choice of variety is based on location, disease resistance, maturity, yield potential and suitability for target market. Soybeans are photoperiod sensitive so choice of variety and appropriate planting date is critical for good yields.

Planting Date

Sowing windows and varieties vary across soybean production regions. In southern NSW, crops should be sown between mid November and mid December so that crops can mature as early as possible (by late March/April). Planting in late December shortens the growing season and reduces total plant dry matter, leading to lower yields and plants maturing in cooler overnight temperatures which delays harvest.

In northern NSW and southern Queensland the planting period is from mid-November through to the end of December. December is the preferred planting month.

In central Queensland the planting period is December through to mid-January – December is preferred.

Soybeans are photosensitive – they flower in response to shortening day length. So planting too early produces a crop that takes longer to flower, and can result in excessive vegetative growth. Planting too late hastens flowering resulting in a crop that produces shorter plants with pods set closer to the ground.

Row spacing

Row spacings of 100cm are used in cotton rotations. However, narrower row spacings (down to 50cm) will increase yield potential by 10 to 20%.

Narrower row spacings should be used when planting late or where weeds are likely to be a problem as the crop canopy closes more quickly.

Plant population

The optimal plant population varies with planting time and row spacing. A population of 300,000 plants per hectare should be used for irrigated crops planted at the optimal planting time. For late plantings this should be increased to 400,000 plants per hectare.

Further Reading

Moore et al 2011 Soybean. In Summer Crop Production Guide 2011, NSW DPI

Ferguson et al 2008 Soybean – growing guide for Queensland, QPIF

4.6 Irrigated mungbeans – best practice guide

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Key points

- Water required varies from 350 to 550 mm
- Mungbeans are sensitive to waterlogging, particularly if irrigated when the soil has been allowed to crack open
- Mungbeans should be planted into a full profile - pre-irrigate if necessary to achieve this.
- Field selection and fast watering practices needed to minimise the risk of crop death through waterlogging.
- Schedule the first irrigation at 7 days prior to budding (R1)
- A second furrow irrigation is usually only needed on lower PAWC soils
- Maintain soil water above 50% PAWC during flowering, podding and seed development
- Irrigation is not necessary beyond the full seed stage (R4)
- Attention to varietal choice, planting date, row spacing, and plant population are critical to achieving a profitable mungbean crop

Plant Water Use

A mungbean crop achieving maximum production will use between 350 and 550 mm of water depending on seasonal conditions.

The amount of water required to produce a mungbean crop is not a fixed value as temperature and relative humidity during the growing period, along with wind and soil moisture, all determine the rate of evaporation from the soil and transpiration from the plant (evapotranspiration or ET_c). The DAFF Queensland free on-line tool CropWaterUse can be used to examine the seasonal variability in crop water requirement for irrigated mungbeans at your location.

Tables 4.6.1 and 4.6.2 summarise the output from CropWaterUse used to estimate the irrigation needed to grow spring and summer mungbeans at three locations Emerald (15 September and 1 January planting dates), Dalby and Narrabri (1 October and 15 December planting dates). The analysis assumes that the crop is fully-irrigated to target maximum yield. An irrigation application efficiency of 75% and a 75 mm irrigation target deficit are assumed. Results show a large variation in seasonal crop water demand, rainfall and irrigation demand between locations and season types.

Figure 4.6.1 shows the daily water use in mungbean which peaks during flowering, podding and seed development (R1 to R4).

The area of irrigated mungbean to plant is a function of mungbean price, available water and your planned irrigation strategy.

Irrigation Strategies

Full Irrigation

Mungbeans are particularly sensitive to waterlogging so good irrigation management is important. They are also a quick maturing crop which reduces their in-crop irrigation requirement. Table 4.6.3 summarises the impact of excessive and inadequate water on mungbean at different growth stages.

The appropriate irrigation strategy varies with the irrigation system used.

For furrow irrigation the key strategies are:

- Select fields with good layout and tail water drainage, enabling fast irrigation events (preferably less than 4 to 8 hours in duration)
- Use high volume beds or hills, with relatively good grades (avoid flat grades)
- Irrigate down every second or alternate furrow and adjust siphon numbers per furrow to aid fast watering

Table 4.6.1. Comparison of average water requirements for spring mungbeans planted on the 15 September at Emerald, and the 1 October at Dalby and Narrabri based on historical weather data (1957 to 2008)

	Narrabri			Dalby			Emerald		
Season Type	**Dry**	**Ave**	**Wet**	**Dry**	**Ave**	**Wet**	**Dry**	**Ave**	**Wet**
Crop ET_c (mm)	523	493	467	483	456	443	448	420	396
In-crop Rainfall (mm)	122	202	314	145	235	331	59	116	215
Irrigation Demand (ML/ha)	5.3	4.1	3.1	4.3	3.2	2.6	4.9	3.9	2.9
No. of Irrigations	5	4	3	4	3	2	5	4	3

Table 4.6.2. Comparison of average water requirements for summer mungbeans planted on the 15 December at Dalby and Narrabri, and the 1 January at Emerald, and based on historical weather data (1957 to 2008)

	Narrabri			Dalby			Emerald		
Season Type	**Dry**	**Ave**	**Wet**	**Dry**	**Ave**	**Wet**	**Dry**	**Ave**	**Wet**
Crop ET_c (mm)	524	501	470	453	435	417	412	387	363
In-crop Rainfall (mm)	116	206	366	161	244	347	131	226	350
Irrigation Demand (ML/ha)	5.3	4.3	3.2	3.7	3.2	2.6	3.6	2.8	2.2
No. of Irrigations	5	4	3	4	3	2	3	3	2

Figure 4.6.1. Average daily water use pattern for mungbean and critical growth stages

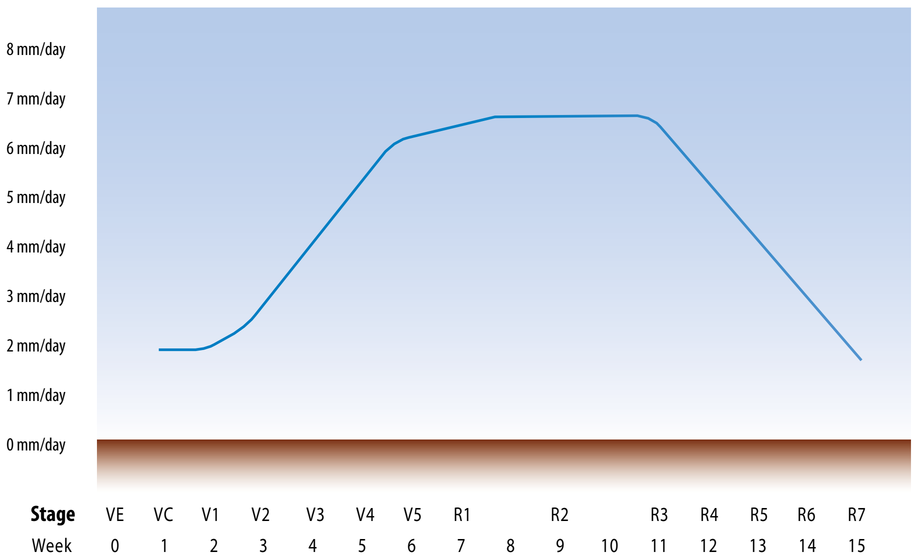

Chart for a 1 October planted crop at Dalby – water use can be as much as 10 to 20% higher under above average temperatures

- If necessary use pre-irrigation to fill the profile prior to planting.
- A single irrigation at around 7 days prior to budding (R1) and before the soil cracks open is usually all that is needed on heavy black earths.
- Irrigating too early can delay or inhibit nodulation and nitrogen fixation. This is usually at 30 to 40 days post-planting.
- Irrigation post flowering (R1) can cause flower drop and plant death through waterlogging.
- Additional irrigation after the start of flowering can cause a succession of flowering events resulting in several stages of pod development in the crop. This makes the timing of desiccation and harvest difficult.

For sprinkler irrigation, the risk of water logging is significantly less as the amount and timing of water application is better controlled.

Irrigations can be scheduled based on soil moisture monitoring using one of the commercial soil moisture monitoring tools available. This equipment can tell you the rate of crop water use and the depth of water extraction.

This can be used to make irrigation scheduling decisions (bearing in mind the importance of minimising waterlogging with this crop).

Irrigation can also be scheduled based on estimation of crop ET_c from weather data. Watersched2, a free online irrigation scheduling tool developed by DAFF Queensland is now available. This tool automatically downloads daily weather data from different locations in Queensland and New South Wales and, using farm-specific inputs, conducts a daily soil water balance and economic analysis to determine when and how much to irrigate.

Figure 4.6.2 is an example of the end of season report generated by WaterSched2 for an irrigated mungbean crop at Dalby in the 2009-10 season. This report summarises the water, crop and economic data for the crop. It provides the WUE indices for predicted and actual yield achieved. The graph at the bottom of the report shows the daily soil water depletion.

During the season, this report provides the information needed to decide on the most appropriate irrigation scheduling strategy in response to crop water requirements, likely economic returns and whole farm water availability.

Limited Water Strategies

If there is a high probability of reduced water allocation and insufficient rainfall, then the yield target may need to be revised down, and supplementary irrigation strategies adopted. Supplementary irrigated crops are 'water limited' – there is not enough water available to fully irrigate the area to be sown. Growers faced with this situation have two main choices:

1. maximise production per hectare by growing an area that can be fully irrigated from the water available
2. grow the largest possible area possible where irrigation is only applied during the most critical growth stages.

Growers wanting to maximise productivity per ML of water will need to strike a balance between these options based on their local conditions and climatic forecasts. Growing a smaller, fully irrigated area of crop may limit the potential upside but avoids the extra costs associated with growing a larger area. On the other hand, yield may be poor if a larger area is planted and seasonal conditions are not favourable.

With mungbeans the first option is preferred given its susceptibility to waterlogging. Ideally mungbeans should be irrigated when the deficit is 30 to 40% of PAWC in the root zone (before significant soil cracking is observed).

For surface irrigated mungbeans the second option is best implemented by planting on a full profile and applying a single irrigation at 7 days prior to budding (R1) and then leaving the crop as a raingrown one. For sprinkler irrigated crops, several smaller irrigations can be timed prior to budding (R1) and during the podding and seed development stages (up until R4).

Table 4.6.3. Critical water management considerations by growth stage for mungbean

Stage	Stage Length (Days)	Description	Water Management Consideration
VE	45 to 55 days	**Emergence** – cotyledons near the soil surface with the seedling showing some part of the plant above the soil surface	If needed, pre-irrigation should have been used to ensure good moisture conditions and an even crop establishment.
VC		**Cotyledon** – cotyledons separate from each other on the upper surface. Unifoliate leaves start to unroll so that the edge of the leaves are not touching each other	
V1		**First Node** – Unifoliate leaves attached to first node are fully expanded and flat	Irrigation during the vegetative stage is unnecessary if the crop was planted into a full profile. Excessive irrigation at this time will produce excessive growth and increase the risk of crop lodging. For furrow irrigation apply the first in-crop irrigation at around 30 to 40 days after planting (7 days before start of flowering)
V2		**Second Node** – 1st trifoliate leaf attached the second node is fully expanded and flat	
V3		**Third node** - 2nd trifoliate leaf at third node fully expanded and flat	
V4		**Fourth node** - 3nd trifoliate leaf at fourth node fully expanded and flat	
V(n)		**N node** – a node is counted when its trifoliate leaf is infolded and its leaflets are flat	
R1	5 to 10 days	**Start flowering** – one flower open at any node on the main stem	For furrow irrigated crops on high PAWC soils (black earths) a single in-crop irrigation should be sufficient. On lower water holding capacity soils a second irrigation during podding may be necessary. For sprinkler irrigated crops, maintain the soil above 50% PAWC during the flowering, podding and seed development stages.
R2		**Beginning pod** – one pod of 1 cm in length is found between node 4 and 6 on main stem	
R3	10 to 15 days	**Beginning seed** – one pod of 5 cm length is found on any of the top 3 nodes on main stem	
R4		**Full Seed** – one pod on any top three nodes has constriction between seed	
R5	15 to 25 days	**Beginning maturity** – one pod on the main stem turns to brown, dark brown or black in colour	Irrigation is unnecessary beyond the full seed stage.
R6		**50% black pod** - fifty percent of pods on the plant mature	
R7		**90% black pod** – ninety percent pods physiologically mature (black or yellow)	

Figure 4.6.2. WaterSched2 End of Season Field Summary report for a fully irrigated mungbean crop at Dalby in 2009-10

WaterSched2

Report Compiled By:
Graham Harris
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End of Season Summary

Field Summary

Farm:	Wallon Park	**Plant Date:**	1/10/2009
Location:	Dalby	**Season:**	2009
Field Name:	Wallon Park	**Length of Season:**	72 days / 1072 GDD
Field Size:	100 ha	**Irrigation Type:**	Surface 100%
Crop:	Early Mungbean	**Irrigation Trigger Deficit:**	75 mm

Water Summary

	mm	ML/ha
Total Irrigation:	200	2
Total Rainfall:	49	0.49
Total Losses:	55	0.55
Starting Soil Water:	190	1.9
Ending Soil Water:	71	0.71
Soil Water Change:	119	1.19
Total Water Input:	368	3.68
Net Water Supply:	312	3.12

Crop Summary

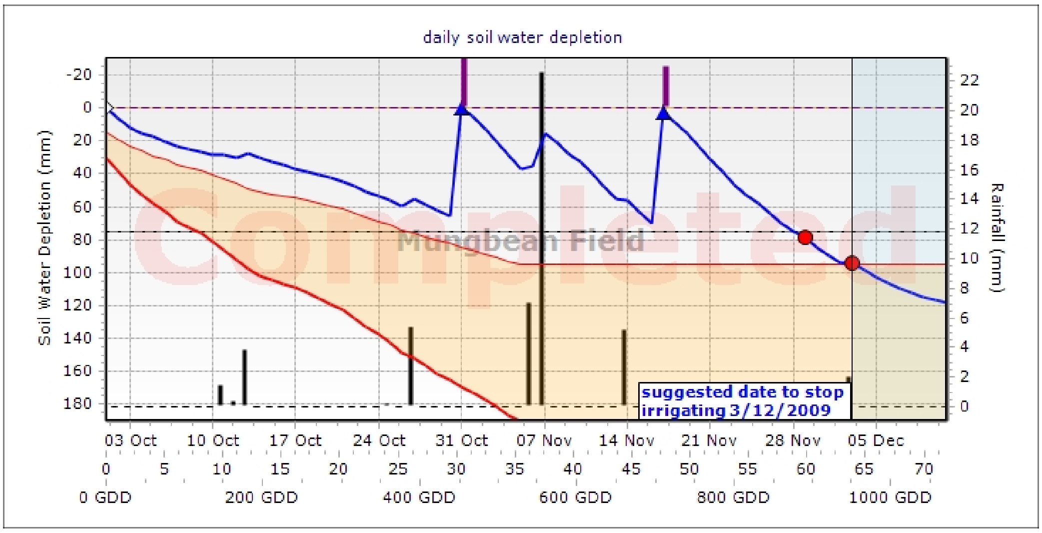
Expected Yield:	2 tonnes/ha
Predicted Yield:	2 tonnes/ha
Actual Yield:	1.8 tonnes/ha
Accumulated ETp:	314 mm
Accumulated ETc:	312 mm

Economics Summary

Price Per Unit:	$700 / tonnes
Variable Costs:	$574 / ha
Gross Margin:	$686 / ha

Water Use Efficiency

	Predicted	Actual	Gross Margin
Total Water Use Index TWUI	0.54 tonnes / ML	0.49 tonnes / ML	$187 / ML
Gross Production Water Use Index GPWUI	0.63 tonnes / ML	0.58 tonnes / ML	$221 / ML
Irrigation Water Use Index IWUI	0.99 tonnes / ML	0.9 tonnes / ML	$343 / ML
Crop Water Use Index CWUI	6.35 kg / mm	5.77 kg / mm	$2.2 / mm



Friday, 16 November 2012 *End of Season Field Summary* **Page 1 of 1**

Agronomy

To achieve high irrigated yields it is necessary to follow good agronomic practices. High yielding crops use water more efficiently than lower yielding crops.

Variety Choice

Choice of variety is based on yield potential and adaptation for specific locations, maturity, powdery mildew resistance, plant height and lodging potential, weather resistance and suitability for target market.

The variety Emerald can produce a high proportion of hard seed which can lead to volunteer plant problems in subsequent cotton crops.

Planting Date

The planting window for mungbeans varies across the irrigated valleys. Generally they can be planted as a spring crop or as a late (summer) crop.

Ideally they should be planted into a full profile to ensure even establishment and even maturity at harvest.

Late October/November plantings are riskier than the preferred late September/early October plantings because of the increased risk of experiencing dry, heatwave conditions at emergence and during flowering.

Row spacing

Row spacings of 18 cm to 100 cm are used. The choice is largely determined by available planting equipment, the existing field layout and tillage practices (whether zero-tilled or cultivated).

Wide row spacings offer a number of advantages which include:

- Greater ability to plant into heavy stubble
- Improved evenness of plant stands and crop maturity as row crop planters are used
- Improved harvestability as plants grow taller with a higher pod set
- Easier access for ground spraying
- Shielded sprayers can be used for weed control
- Input costs can be reduced by band-spraying

Where the yield potential is greater than 1 t/ha, narrower row spacings have a yield advantage – around 10 to 15% in favour of narrow rows as yield potential approaches 2 t/ha.

In surface irrigated fields yield potentials can be maximised by using multiple rows planted onto 2 m beds as opposed to 1 m row configurations.

Plant population

For narrower row spacings, aim for a target population of 30 to 40 plants per square metre. Populations above these increase the risk of lodging. Crystal, Satin II, White Gold, Emerald and Green Diamond are more resistant to lodging at these higher populations than other varieties.

At 1 m row spacings aim for 20 to 25 plants per square metre – higher populations will exacerbate lodging.

If planting after mid-January yield potential is reduced. This is because the crop flowers around 35 days after planting, producing short plants that fail to achieve canopy closure. In this situation increase the planting rate by 5 kg/ha.

Further Reading

Cumming, G. and Gentry, J. 2010 Certified Mungbean Agronomy Course 2010, The Australian Mungbean Association, Pulse Australia and DAFF Queensland

Gentry, J. 2009 Mungbean Management Guide, QPIF

4.7 Irrigated barley – best practice guide

Graham Harris
DAFF Queensland

Key points

- Seasonal water requirement varies from 320 to 470 mm
- A full irrigation strategy or limited water irrigation strategy can be used
- The period leading up to and including flowering (which takes place at booting in barley) is the most sensitive to water stress.
- Good agronomic practices are needed to maximise production and minimise lodging risk
- Good nitrogen management needed to meet malting barley protein specifications
- Aim to establish 100 plants per m^2
- Planting on rainfall preferred over pre-irrigation and watering up which can delay planting and produce excessive biomass respectively
- Irrigate to encourage secondary root development if needed
- Foliar disease can be a significant problem in barley – varietal choice, seed dressings and crop rotation needed to manage these

Plant Water Use

The amount of water required to produce a barley crop with maximum yield is not a fixed value as temperature and relative humidity during the growing period along with wind and soil moisture all determine the rate of evaporation from the soil and transpiration from the plant (evapotranspiration or ET_C). In favourable seasons the water requirement may be as low as 320 to 420 mm whereas in a warmer dry year this requirement could be up to 360 to 470 mm to produce maximum yields.

The DAFF Queensland free on-line tool CropWaterUse can be used to examine the seasonal variability in crop water requirement for fully irrigated barley at your location (see Table 4.7.1).

It shows the irrigation demand for 1 June planted barley at three locations (Narrabri, Dalby and Emerald), assuming that the crop was fully-irrigated to target maximum yield. An irrigation application efficiency of 75 % and a 75 mm irrigation target deficit are assumed. Results show a large variation in seasonal crop water demand, rainfall and irrigation demand between locations and season types.

Figure 4.7.1 shows the daily water use in barley which peaks during flowering and milk development (GS60 to GS70).

Moisture availability at this stage is critical to the yield of the crop. Moisture stress for more than a few days during this period will result in lower grain yield and quality.

The area of irrigated barley to plant is a function of barley price, available water and your planned irrigation strategy.

Irrigation Strategies

Full Irrigation

For fully-irrigated barley where water is not limited, the aim is to maximise yield by scheduling irrigations to match crop water demand and avoid crop stress during the entire growing season. This requires the close monitoring of soil moisture once secondary root development has been completed (normally GS31).

In order to avoid crop stress, do not allow soil water to fall below 50% of plant available water capacity (PAWC). This is commonly referred to as the 'refill point'.

Once below 50% of PAWC, crops use more energy extracting the remaining soil water. Plant growth and yield potential will fall considerably if soils are allowed to dry down beyond this threshold.

Table 4.7.1. Comparison of average water requirements for barley planted on the 1 June at Narrabri, Dalby and Emerald, based on historical weather data (1957 to 2008)

	Narrabri			Dalby			Emerald		
Season Type	Dry	Ave	Wet	Dry	Ave	Wet	Dry	Ave	Wet
Crop ET_c (mm)	383	352	301	410	387	363	420	405	375
In-crop Rainfall (mm)	112	196	319	89	158	238	26	77	186
Irrigation Demand (ML/ha)	3.6	2.3	1.8	4.1	3.4	2.6	4.8	4.3	3.1
No. of Irrigations	4	2	2	4	3	3	5	4	3

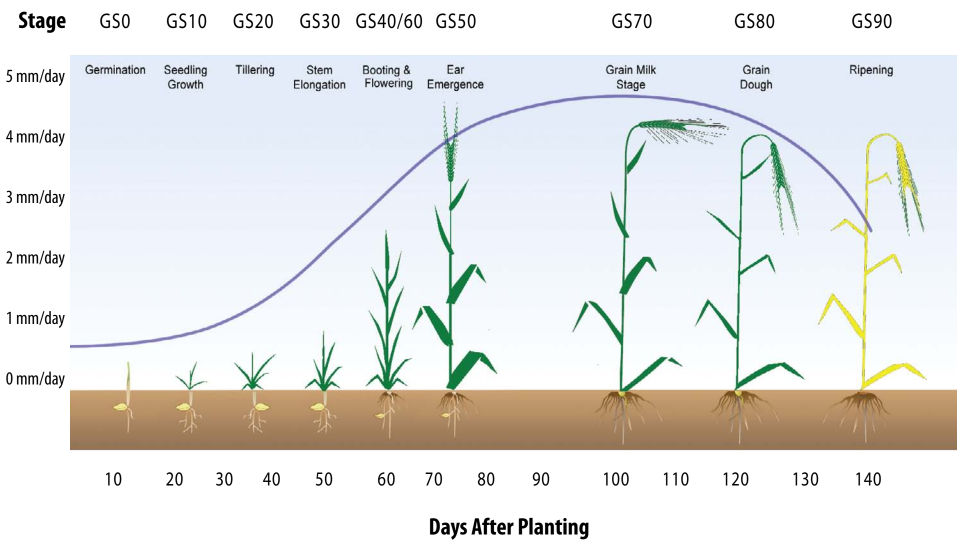
Make sure water is available for 2 to 3 days before the crop reaches its refill point. The reproductive growth phase typically coincides with an increase in temperature and an acceleration of plant water use. Any delay in water application can cause significant yield losses. As barley flowers in the boot stage it is important that a full profile is available to the crop at booting.

The period leading up to and including flowering is the most sensitive to water stress. Stress at this time will reduce the number of heads per plant, head length, and number of grains per head. It can also restrict root growth. Yield losses from excessive water deficits at this time cannot be recovered by later irrigations.

Key points to consider when scheduling irrigation for fully-irrigated barley are:

- crop stress must be avoided. ET_c is usually linearly related to crop yield. Stressing the crop at any stage of development reduces ET_c and yield. This yield loss cannot be recovered by irrigating at a later time. To avoid crop stress, it is important to know when to irrigate and how much water to apply. Table 4.7.2 summarises the water management considerations for each growth stage of barley.

Figure 4.7.1. Barley water use pattern and growth stages



- The application of a fixed water depth at each irrigation can lead to deep drainage losses. It is not necessary to refill the soil profile at each irrigation. Overhead systems are especially suited to application of small irrigation depths, but application depths can also be reduced with surface irrigation systems by increasing siphon flow rates and reducing irrigation runtimes.
- Crops can only extract water from their effective root zone. Therefore, the depth of soil wetted by irrigation needs to be adjusted during the season to respond to increases in root zone depth and irrigation wetted front should not go deeper than the effective crop root zone.
- The soil water deficit to trigger irrigation also depends on the depth of the root zone and needs to be adjusted during the season. Both the ET_C rate and the soil water deficit change daily, so irrigation frequency needs to be adjusted in response to these changes.
- The desired soil water deficit and the irrigation frequency also depend on the irrigation system capacity (mm/day). This highlights how much water the irrigation system can apply in one day, allowing for system breakdowns or maintenance. The greater the system capacity, the greater the soil water deficit that can be replenished quickly.

Irrigations can be scheduled based on soil moisture monitoring using one of the commercial soil moisture monitoring tools available. This equipment can tell you the rate of crop water use and the depth of water extraction. This can be used to make irrigation scheduling decisions.

Irrigation can also be scheduled based on estimation of crop ET_C from weather data. Watersched2, a free online irrigation scheduling tool developed by DAFF Queensland is now available. This tool automatically downloads daily weather data from different locations in Queensland and New South Wales and, using farm-specific inputs, conducts a daily soil water balance and economic analysis to determine when and how much to irrigate.

Figure 4.7.2 is an example of the end of season report generated by WaterSched2 for a fully irrigated barley crop at Dalby in the 2009 season. This report summarises the water, crop and economic data for the crop. It provides the WUE indices for predicted and actual yield achieved. The graph at the bottom of the report shows the daily soil water depletion during the season.

During the season this report provides the information needed to decide on the most appropriate irrigation scheduling strategy in response to crop water requirements, likely economic returns and whole farm water availability.

Correct timing of the last irrigation will ensure adequate grain fill and also reduce the risk of lodging and harvesting delays. It should be applied around the soft dough stage (GS85) if readily available water has been used to 60 to 90 cm soil depth. This will produce maximum yields on clays and loams, minimise black tip and provide best test weights. Irrigating beyond this stage will generally not improve yields, will lower test weights and increase black tip. It will also reduce water use productivity.

Limited Water Strategies

If there is a high probability of reduced water allocation and insufficient rainfall then the yield target may need to be revised down and supplementary irrigation strategies adopted. Supplementary irrigated crops are 'water limited' – there is not enough water available to fully irrigate the area to be sown. Growers faced with this situation have two main choices:

1. maximise production per hectare by growing an area that can be fully irrigated from the water available
2. grow the largest area possible where a single in-crop irrigation can be applied.

Growers wanting to maximise productivity per ML of water will need to strike a balance between these options based on their local conditions and climatic forecasts. Growing a smaller, fully irrigated area of crop may limit the potential upside but avoids the extra costs associated with growing a larger area. On the other hand, yield may be poor if a larger area is planted and seasonal conditions are not favourable.

In general, maximum crop productivity under irrigation is achieved when good soil moisture is available at sowing and then one or two supplementary spring irrigations are applied (one irrigation in wetter districts such as the Liverpool Plains, and two irrigations in drier areas such as Emerald and Goondiwindi).

If a large area of barley must be planted as part of a rotation, and only a single irrigation is possible, the best timing is one which applies water at the most critical growth stage – from stem elongation (GS30) through to flag-leaf emergence (GS39).

Table 4.7.2. Critical water management considerations by growth stage for barley

Zadoks Development Stage		Water Management Consideration
0	**Germination**	Adequate soil moisture essential to establish desired plant population. Waterlogging can increase seed mortality
1	**Main stem leaf production** Seedling Stage is the growth stage from emergence until the plants begin to tiller	Early weed control will conserve plant available water.
2	**Tiller production** Tillering usually starts when the plant has 3- 4 leaves. A (short growth cycle) barley plant will typically produce 7-8 leaves on the main stem before stem elongation occurs.	Early weed control will conserve plant available water. Good nutrient and water supply are determining the potential number of heads produced by the crop
3	**Stem elongation** Main stem node production. The maximum potential number of florets (and therefore maximum yield potential) is now set. The tillers produced last during stem elongation will often die. The final number of productive tillers depends on the conditions.	Good nutrient and water supply are determining yield potential. If stress during stem elongation is followed by heavy water application, barley has the ability to produce new tillers and additional heads. However these additional heads will delay harvest and the risk of losses from lodging and non-uniform ripening usually increases. Soil water depletion should not exceed 50% of PAWC.
4	**Booting** By booting each plant should have 2-3 productive tillers depending on growing conditions and crop density.	Pollen formation is sensitive to stress so water deficits and high temperatures at this time will decrease the number of seeds that form and may reduce yield. Soil water depletion should not exceed 50% of PAWC.
5	**Heading** The spike (also called the head or ear) is emerging from within the flag leaf.	
6	**Flowering** Pollen is being released and the individual grains are being fertilized. Flowering takes place before or during head emergence – barley flowers are primarily self-pollinating.	
7	**Grain milk stage** When the grain is squeezed, a milky solution is apparent.	
8	**Grain dough stage** When squeezed, the grain will still deform slightly, but no liquid is apparent.	Yield is almost set, but water stress will still reduce grain size and yield. Soil water depletion should not exceed 50% of PAWC.
9	**Ripening** Grain is hard and firm and ready for harvest. Grain is best harvested below 14% moisture content. Wetter grain (>14% moisture content) has storage problems.	Lodging will reduce harvestable grain yield.

Figure 4.7.2. WaterSched2 End of Season Field Summary report for a fully irrigated barley crop at Dalby in 2009

WaterSched2

Report Compiled By:
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End of Season Summary

Field Summary

Farm:	Wallon Park	**Plant Date:**	1/06/2009
Location:	Dalby	**Season:**	2009
Field Name:	Wallon Park	**Length of Season:**	131 days / 1894 GDD
Field Size:	100 ha	**Irrigation Type:**	Surface 100%
Crop:	Medium Barley	**Irrigation Trigger Deficit:**	75 mm

Water Summary

	mm	ML/ha
Total Irrigation:	300	3
Total Rainfall:	63	0.63
Total Losses:	107	1.07
Starting Soil Water:	230	2.3
Ending Soil Water:	79	0.79
Soil Water Change:	151	1.51
Total Water Input:	514	5.14
Net Water Supply:	406	4.06

Crop Summary

Expected Yield:	6 tonnes/ha
Predicted Yield:	5.9 tonnes/ha
Actual Yield:	5.75 tonnes/ha
Accumulated ETp:	412 mm
Accumulated ETc:	407 mm

Economics Summary

Price Per Unit:	$150 / tonnes
Variable Costs:	$537 / ha
Gross Margin:	$325.5 / ha

Water Use Efficiency

	Predicted	Actual	Gross Margin
Total Water Use Index TWUI	1.15 tonnes / ML	1.12 tonnes / ML	$63 / ML
Gross Production Water Use Index GPWUI	1.45 tonnes / ML	1.42 tonnes / ML	$80 / ML
Irrigation Water Use Index IWUI	1.97 tonnes / ML	1.92 tonnes / ML	$109 / ML
Crop Water Use Index CWUI	14.51 kg / mm	14.13 kg / mm	$0.8 / mm

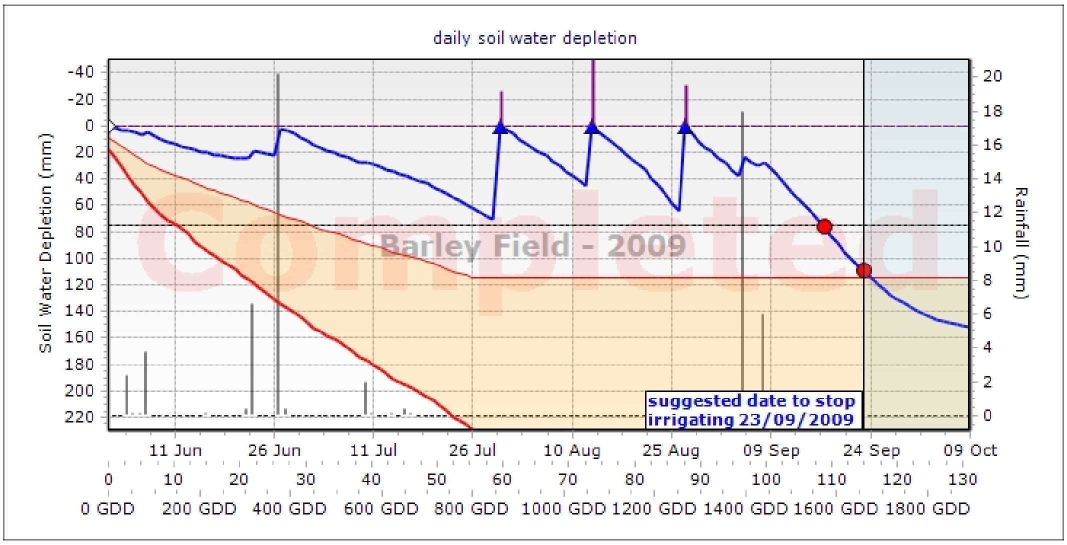

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Table 4.7.2 summarises the impact of water stress on barley at different growth stages.

The best timing for a single in-crop irrigation of around 1 ML/ha is from early stem-elongation through to flag-leaf emergence. It will still have time to help the crop develop a little more biomass, yet will also leave some soil water for flowering and early grain filling. The best timing of a single irrigation within a particular season will vary depending on the timing of in-crop rainfall, and stored water at sowing.

If two irrigations (or 2 ML/ha) is budgeted, then an irrigation applied at early to mid-stem elongation (GS30 to GS33) and again between flag-leaf (GS39) and the first awns being visible (GS49) – this is because flowering in barley takes place in the boot and early ear emergence stages.

Agronomy

To achieve high irrigated yields and meet market quality requirements it is necessary to follow good agronomic practices.

Barley is particularly prone to lodging – this is exacerbated by targeting high yields under irrigation. Lodging occurs mostly after ear emergence and can significantly affect grain yield and quality. Factors affecting lodging potential include:

- variety lodging susceptibility;
- shallow root systems due to abundant soil moisture or frequent irrigations;
- subsoil constraints like sodicity or compaction;
- high nutrition levels causing plants to grow too quickly; and,
- severe weather during crop ripening.

The range of agronomic practices discussed below is aimed at maximising yield and controlling lodging through canopy management.

Nutrition

Management of nitrogen availability is vital to achieve optimal yields and quality in barley. The level of nitrogen and plant available water will impact strongly on yield and protein having potentially a major impact on crop return. Unlike wheat where premiums are available for high protein, barley premiums for malting require moderate proteins of 9 to 12%. If you target around 12% protein this will also be maximising yield potential for barley.

A large percentage of Queensland's barley crop is classified as feed with protein levels above 12%. Older cultivation or double crop situations with lower soil N supplies can produce malt-grade barley especially in a good season, however, skill is required to balance the requirement for nitrogen to maximise yield without over fertilising and increasing the protein level.

A rule of thumb used by some to grow malting barley is to use 0.4 kg of nitrogen for every mm of available soil moisture. Thus if there is 400 mm of available moisture (stored soil water plus irrigation), this will require 160 kg of nitrogen to produce a barley crop with protein between 8.5 and 12 per cent. In high yielding years, grain protein can be reduced through nitrogen dilution as grain yield increases.

Test soil for starting nitrogen (to 90 cm depth) and phosphorus (to 20 cm depth) in April/May before sowing.

Use the nitrogen calculation guidelines in the Barley production in Queensland website to develop your nitrogen nutrition program.

Low phosphorus levels will affect crop establishment and can delay flowering which affects the yield potential and grain filling time of the crop. It is recommended that starter fertiliser with phosphorus containing 10 to 20 kg P/ha be used unless soil P levels are very high.

Variety Choice

Choice of variety is particularly important. Only certain varieties are accepted for malting. Select varieties with a proven performance in your region.

It is particularly important to consider the standability of varieties and their post-ripe straw strength to minimise losses from lodging. Susceptibility to the foliar diseases leaf rust, net blotch and powdery mildew is also an important consideration in choosing the variety to grow.

For the latest information on available barley varieties refer to the most recent Barley – planting and disease guide.

Plant population

For maximum yield potential a plant population of 100 plants per square metre or higher is needed. The required seeding rate will be between 40 to 60 kg/ha depending on number of seeds per kg and estimated establishment rate. Plant populations below 80 plants per square metre will have reduced yield potential and provide less weed competition.

Seedbed Preparation

Seedbed preparation has a significant impact on seedling emergence and yield potential. Following pupae-busting, tillage should be used to prepare a new seedbed that is free of clods and cotton stubble. Seedbed tilth needs to be in an optimum condition for seed placement and emergence.

Planting Date

Planting time is a management compromise that balances having the crop flowering soon after the last heavy frost, but still early enough to allow adequate grain fill before the heat in spring. At flowering barley can tolerate a 1°C lower frost than wheat. But a frost of -4°C at head height during flowering can cause yield losses of 5 to 30 per cent.

Varieties differ in the time they take from planting to flowering. Select the planting time for your variety that ensures it will flower after there is little chance (1 in 10 years) of a frost occurring.

Sowing early within the optimum range is better suited to low-N paddocks where canopy can be managed through delayed N application, and when irrigating up.

Establishment

Ideally barley should be planted after a rainfall event which provides planting moisture and ensures seed germination and establishment. This provides the best opportunity to achieve high yields (particularly if starting soil N levels are low). In this situation a uniform plant stand can be achieved and you can manage early season canopy growth and allow an irrigation to ensure secondary root development.

Pre-irrigation is risky as sowing can be delayed if rain occurs. However, establishment can be better in this scenario than if a paddock is dry-sown and watered up.

If the profile is completely dry at planting the only option may be to plant shallow and water-up. This is the least desirable option, particularly if starting soil-N levels are very high. Often, in water-up situations, plants still do not initiate secondary root growth and require further irrigation during tillering which can result in excessive early season biomass. This can predispose the crop to lodging, particularly where soil starting N levels are high.

Secondary Root Growth

Assess soil moisture status at 25 to 30 days after emergence. If there is dry soil below the sowing depth of seed, apply an irrigation to encourage secondary root development on low soil-n paddocks. Early secondary root development will enhance water and nutrient uptake.

Disease Management

Choice of variety is critical in managing the risk of disease losses. The most significant diseases are the foliar ones – powdery mildew, leaf and stem rust, net blotch and spot blotch. Choose varieties with the highest levels of resistance (note there are no Spot blotch or Stem rust resistant varieties currently available).

Treat seed with appropriate fungicidal dressings as smuts and net blotch (net form) may be seed borne.

Do not plant barley on barley as stubble borne spores are the main source of infection for net blotch and spot blotch.

Further Reading

Franckowiac, J.,Sturgess, J. and Platz, G.2012 Barley – planting and disease guide 2012, DAFF Queensland

McIntyre, K. 2010 Barley production in Queensland, DAFF Queensland

Section 5

Irrigation systems

5.1 Selecting an irrigation system

This material is summarised from NSW DPI PROwater© Irrigation Training Series Module 2: Selecting an irrigation system.

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Key points

- A number of different surface and pressurised irrigation systems exist, offering a range of advantages and limitations.
- It is important to consider different irrigation system alternatives in light of your overarching enterprise goals.
- The most appropriate irrigation system for a particular situation should consider the topography, soils, crop water requirements, energy, labour and irrigation performance.
- System capacity is a key measure in determining the suitability of an irrigation system to a particular crop type and location.
- The system selection process can be complex.
- Any system should be designed by an appropriately qualified irrigation designer to ensure that it operates to its potential.

Introduction

Selecting an irrigation system requires you to determine which one is most suitable for your situation. In many cases, no single best solution may exist, as each system has their particular advantages and disadvantages and no two situations are exactly the same.

Selecting a suitable system is a process of balancing a number of key parameters that are specific to each irrigation enterprise. These include the enterprise goals, area of land, topography, soils, water supply, climate, crops, finances, regulatory requirements and management style.

Investigating existing systems that are working well in situations similar to yours is usually very helpful.

This chapter provides an overview of the principles and processes and the opportunities and constraints that the various systems allow.

Types of irrigation systems

Irrigation systems can be categorised into two broad groups:

- Surface irrigation systems – where water is applied to the root zone by flow over the soil surface by gravity, e.g., furrow, border check, contour bay.
- Pressurised irrigation systems – where water is applied through a pressurised pipe system and emitters or sprinklers, e.g., centre pivot, lateral move, travelling irrigator, drip.

No system type is inherently better than another; each individual irrigation system should be selected and designed depending on a range of factors specific to each site.

Surface irrigation systems

Border check; consists of a sloping strip of land, level across the strip, bordered by low check banks. Laser-levelled fields are essential for even water distribution. Slopes range from 1:100 to 1:1200, common bay lengths are 300 to 600 metres, and common bay widths are 30 to 100 metres. Bay inlets are usually gates or siphons, and the lower ends of the bays generally drain directly into a shallow tail water channel.

Furrow or bed irrigation (WATERpak Chapters 5.2 and 5.3). Water flows down narrow furrows between crop rows or beds. Laser-levelling of fields is usually required to obtain a consistent slope down the field which is essential for even irrigation along the furrows and good drainage but does not need to be as precise as for Border Check systems. Slopes range from 1:500 to 1:1500, common furrow lengths are 300 to 1000 metres, and furrows are usually V-shaped. For furrow irrigation, furrows are usually 1 or 2 metres apart, and for bed irrigation they can be up to 4 metres apart. Inlets are usually siphons or through-the-bank pipes. The lower end of each furrow generally drains directly into a tail water channel.

Contour irrigation; fields are laid out with banks formed on topographic contours and have slope in the lateral direction (i.e., across the width of the bay) but not in the longitudinal direction (i.e., down the length of the bay). Contour irrigation is usually reserved for ponded crops like rice but is also used to grow rotation crops such as pasture or wheat. Precise laser-levelling of fields is essential to obtain a consistent, small slope.

Figure 5.1.1. Border Check irrigation system (image: G. Giddings)

Figure 5.1.2. Furrow irrigation system

Figure 5.1.3. Bed irrigation system

This is necessary to provide an even depth of water when ponded, good drainage when the water is released, and even irrigation for the rotation crops. For rice crops, the soil should be heavy clay that limits deep drainage. Slopes commonly range from 1:1000 to 1:2000. Common bay lengths are 400 to 450 metres with check banks at 50 mm contour intervals. Inlets are usually gates or 'stops'. Each bay may drain into the next with the last bay in a sequence draining into a tail water channel, or each bay may be drained directly into a tail water channel.

Bankless channel or side-ditch delivery (WATERpak Chapter 5.4). Water is applied and drained from the bottom of the slope. These systems have a supply channel running with the slope down one side of the irrigation block without a bank on the inside of the bay. Checks are placed across the supply channel at each contour bank to control flows. The bed of the channel is below the level of the bay and acts as both a supply and drain. Longitudinal slopes range from 1:5000 to level, with 1:10000 a commonly used slope.

These very flat grades provide enough slope to drain water from the field without creating excessive water depths at the inlet. Water moves up the slope when being applied and drains back to the supply channel to augment flow to the next downstream bay. For flat-planted systems a lateral slope is sometimes introduced, whilst in bed or furrow configurations there is zero side slope. This creates a terraced system with a step between the bays of 0.1 to 0.2 m.

Figure 5.1.4. Contour irrigation systems. (Foreground shows a conventional system with check banks formed along the natural contours. Background shows land-formed fields that are rectangular in shape and with check banks formed along the altered contours.)

Figure 5.1.5. Bankless channel system commencing irrigation (Photo: M. Grabham)

Pressurised irrigation systems

Spray lines – fixed. Fixed spraylines are often used for vegetable crops, permanent horticultural plantings and sometimes for pasture irrigation. Water is delivered through a permanent, buried mainline. The irrigation area is usually divided into a number of blocks with a sub-main for each block running off the mainline. Sub-mains are usually permanent (buried) but may be portable (laid on the surface). Water reaches the crop though a grid of surface laterals fitted with sprinklers which are generally of the 'knocker' type and provide from 5 to 20 mm per hour of water and operate between 200 and 450 kPa.

Figure 5.1.6. Fixed Overhead irrigation system

Spray lines – movable. Hand-shift spraylines consist of lengths of aluminium irrigation pipe with quick connect and release couplings at both ends and a sprinkler at one end. These are moved and fitted together by hand and usually supplied from a riser attached to a buried sub-main. The sprinklers also may be mounted on risers to get above a crop. Pressure ranges from 150 to 450 kPa. They are used for irrigating pasture or short crops such as lucerne and vegetables. This system is suitable for regular or irregular shaped fields.

End-tow spraylines are similar to hand-shift except each coupling is fitted with a skid or pair of small wheels. This allows the entire length of connected pipes to be towed by the end from one position to the next, reducing the labour requirement. The couplings have to be more robust than for hand shift. These systems must be moved empty of water, so the couplings have valves for draining the pipes. The direction of tow must be in line with the pipes if fitted with skids, so movement can only be directly to an adjacent field. If wheels are fitted, movement can be straight ahead to another field or at an angle of 45° in the same field in a zigzag pattern, towed alternatively from opposite ends. This system is best suited to rectangular fields with gentle topography.

Side-roll systems are also similar to hand-shift except each length of pipe is mounted through the centre of a large wheel of about 2-metre diameter. The entire length of pipe can then be shifted to the next position in a few minutes by rolling it sideways. A small motor and drive mechanism is usually fitted at the centre of the length of pipes to eliminate all manual effort. The sprinklers are mounted on a swivel so they remain upright. The system must be moved empty of water, so the couplings have spring-loaded valves that open when the pressure has dropped, allowing the water to drain out. This system is best suited to rectangular fields with gentle topography.

Travelling guns and booms. These irrigators come in two forms: with a soft hose and a cable drum, or with a hard hose drum. They can be fitted with a single 'big gun' sprinkler or with a boom which has a number of emitters along it. The booms use sprinklers that are commonly fitted to other sprinkler systems such as centre pivots or spray-lines. 'Big-gun' travellers require high pressure to operate properly, so are high consumers of energy.

Rotary boom irrigators are similar except that the big gun sprinkler is replaced by a galvanised boom fitted with medium to low pressure sprinklers. The boom is rotated by the discharge from the sprinkler nozzles, and the rotation provides the energy to operate the drive mechanism and cable winch. Various sprinkler combinations (big gun, rotating, and low pressure) can be used.

Working pressures for travelling guns and booms range from 70 kPa to 500 kPa.

These systems are commonly used to irrigate pastures and lucerne, but machines with elevated wheels can be used on taller crops.

Figure 5.1.7. Side-roll sprayline system

Figure 5.1.8. 'Big-gun' Travelling irrigator

Figure 5.1.9. Rotary Boom Irrigator

Centre pivot & lateral move (WATERpak Chapter 5.5). Centre pivot and Lateral (or Linear) move (CPLM) systems are both a mobile pipeline and a platform for water application devices. A centre pivot is a travelling irrigation line that is fixed at one end and the other end rotates around it. They are often around 400 metres long and commonly have 4 to 12 towers that position the pipeline high above the ground. A centre pivot's main distinction is a fixed centre tower containing a water supply point and power source around which the other spans and towers rotate. A major advantage of centre pivots is that they cover large areas at low operating pressures, thus minimising pumping costs. These systems can operate over undulating country (as shown in figure 5.1.10) as long as pressure regulators are fitted to each sprinkler.

Figure 5.1.10. Centre Pivot irrigation system (Photo: E. Parr)

Lateral move machines are constructed in a manner similar to centre pivots except that they do not have a central fixed supply point. Instead, they have the water supply point located either in the middle (centre-feed) or at one end (end-feed) of the machine on a cart-tower assembly which usually contains a mobile power plant and the pump. Lateral move machines that are supplied from open channels are provided with a large lift pump, while hose-supplied systems are fitted with an attachment point for connection to the water supply pipe line via a hydrant and a flexible water delivery hose. They are commonly 800 to 1000 metres wide with average run lengths greater than 1 kilometre creating an irrigated area of around 165 ha but can be used on areas down to 50 ha or over 300 ha. Lateral Moves require level, rectangular blocks. Run lengths can be several kilometres with separate sections irrigated each season or in rotation.

CPLM machines may be fitted with end-guns to increase the irrigable area for a small extra cost, but careful design is required to ensure acceptable distribution uniformity. End-gun systems typically require on-board booster pumps to provide sufficient nozzle pressure, increasing energy usage.

The direction and speed of CPLM systems is governed by the end towers. With electric machines, the drive points on the intermediate towers start when they get slightly behind and stop when they get slightly ahead. With hydraulic units, the towers are in constant motion but at varying speeds according to oil flow and pressure. The intermediate towers have mechanisms to control the oil flow or pressure, speeding them up when slightly behind and slowing them down when slightly ahead.

Drip irrigation (WATERpak Chapter 5.6). Drip irrigation systems are so named because they use low flow-rate emitters. Above ground drip systems are commonly used in permanent horticulture (vineyards, fruit trees, etc.) while sub-surface drip is installed for pasture or broad acre crops.

Because drip systems apply water at precise rates near or at the root zone, and losses through evaporation runoff or deep drainage are almost nil, irrigation efficiency can be very high.

Drip systems are usually installed permanently so components are not moved to various positions. This means they can be easily automated. Both of these features reduce labour and are often sufficiently appealing in themselves for farmers to choose this system over others, let alone the greater water efficiency and despite the significantly higher cost.

Water filtration is required to remove contaminants and prevent emitters clogging. The equipment required depends on the water quality and may be up to a third of the total cost of the system.

Water delivery to the field is usually achieved through PVC or poly main supply lines and sub-mains. Small diameter plastic lines placed within the crop are called laterals. These are laid parallel to each other and are connected to the sub-mains. The plastic emitters or drippers are typically built into the lines during manufacture, though emitters can be installed afterwards.

For terrain with high slopes, pressure compensating emitters may be necessary to ensure even application.

This animation explains the steps in sub-surface drip irrigation.

Figure 5.1.11. A typical drip layout (Netafim)

Micro-irrigation. These systems are suited to under-tree irrigation and some intensive horticulture enterprises like ornamental flowers and vegetables. Individual emitters are placed adjacent to trees or vines so as to deliver water to the area of the plant rootzone rather than the entire field.

There are two types of emitters: fixed spray head (known as a micro-jet or micro-spray) and small rotating sprinkler (usually called a mini-sprinkler). Micro-jets provide between 20 and 200 litres per hour at operating pressures of 100 to 250 kPa. Their diameter of coverage ranges from 1 to 7 metres. Mini-sprinklers provide up to 600 litres per hour at operating pressures of 150 to 350 kPa. Their diameter of coverage ranges from 2 to 12 metres.

Both types require filtration to avoid blockages due to their small openings and passages. Filter selection is determined by the quality of the water used.

Figure 5.1.12. Micro-spray under a citrus tree

Irrigation System Considerations

Enterprise goals

The goals of enterprises may vary widely. Factors affecting goals can be economic, environmental and social.

- Economic factors may include available capital, cash flow and desired profitability.
- Environmental factors may include biodiversity, vegetation, habitat, soil health, water quality, available water volume, water extraction rate, pollutants and emissions.
- Social factors may include community viability, aesthetic and amenity value or relationships with neighbours.

The following steps do not consider how to set your enterprise goals and assume that your goals remain consistent. It is important that you weigh up each step in light of your goals.

Collect basic information

Selection and design of an effective irrigation system is only as good as the information that goes into it. Time spent carefully considering the intended use of the system and gathering relevant information is essential for a satisfactory result.

The first step is to collect basic farm information.

Physical Location

- current and proposed irrigated areas
- contour lines
- farm and field boundaries
- water source(s)
- earthworks, laser levelling, etc.
- soil types, infiltration rates, problems, etc.
- current agricultural practices
- power lines, roadways, buildings, easements, trees, other features and obstacles

Water Supply

- quantity available, incorporating; the volume of licensed entitlements (river and groundwater), reliability, on-farm storage capacity, overland flow harvest, rainfall, effluent water, etc.
- maximum flow rate
- quality over time
- cost of water

Irrigable Area

- crops intended to be grown, their suitability for the climate, soils, water quality, etc.
- seasonal peak crop water use (peak ETc)
- total irrigation requirements
- maximum depth of water applied per irrigation
- irrigation frequency and cycle
- required irrigation system capacity
- irrigable area to be developed

Topography

The topography is the first factor for deciding whether irrigation is a suitable option. Generally, flat land is best while very steep or highly variable slopes may preclude irrigation.

Surface irrigation requires flat land with small slopes. Flatter slopes are better suited to heavier soil types. Pressurised systems suit a wider range of slopes which can be quite steep.

For furrow, border check and contour layouts the slope should all be in the same direction, otherwise drainage will be a problem.

For centre pivots, slope does not need to be in the same direction. Lateral moves need flat fields or a constant rise or fall in the direction of travel otherwise steering performance will be affected. CPLM systems used to grow row crops must be 'cut to drain' so that rainfall runoff does not run along furrows and pool at low areas. Runoff must have a pathway to escape from crop rows when required.

For surface systems, topography will influence the infiltration opportunity time and thus the uniformity of infiltration. For pressurised systems topography will influence the pressures required to pump the water.

Soils

The soil type(s) and their characteristics are the most important factor in selecting an irrigation system. They have a major impact on whether irrigation is a suitable option in the first place, and they set the main limits on the proposed system.

For surface irrigation, the soil is the main regulator of the water applied to the root zone. The application rate of the system is set by the infiltration rate of the soil. Sandy soils have high infiltration rates. Clay soils usually have low infiltration rates. Loam soils are somewhere in between. Table 5.1.1 shows general infiltration rates of various soil types.

Table 5.1.1. Average infiltration rates for some soil types

Texture group	Application rate (mm/h)		Infiltration rate range (mm/h)
	Average soil structure	Well-structured soil	
Sands	50	-	50 – 700
Sandy loam	30	45	50 – 700
Loam	30	45	5 – 300
Clay loam	10	25	2.5 – 300
Light clay	2.5	5	0.5 – 40
Medium-heavy clay	2.5	5	0.1 – 40

Adapted from Charman, P.E.V. and B. W. Murphy (eds) 2000, Soils: their Properties and Management, in association with the NSW Department of Land and Water Conservation, 2nd ed, Oxford University Press, Melbourne.

Most soils have a somewhat higher infiltration rate when dry, which decreases as the moisture content increases. This is particularly evident with cracking clay soils that are common in most cotton growing areas.. These can have infiltration rates like sand when dry, reducing to very low rates like heavy clay when wet. The degree of this variation is determined by how strongly cracking the clay is; different base minerals and different mixtures of clay, silt and sand create this variation.

Furthermore, variations in soil across the field and below the surface cause variations in the infiltration rate, resulting in variations in the amount of water reaching the root zone.

Surface irrigation is therefore best suited to soils with little variation. The best soils for most surface irrigation systems are deep clays with strong self-mulching and cracking characteristics.

Pressurised irrigation is better for soils with higher infiltration rates and/or fields with a lot of soil variation. The application rate of the irrigation system should be designed to match the infiltration rate of the soil, taking into account the initial and steady-state infiltration rates. For systems that apply water for a short amount of time (e.g., CPLM), the initial rate is most relevant, while for systems that apply water for several hours, the steady-state rate is most relevant.

Crop Water Requirements and System Capacity

Your irrigation system must be designed to meet the maximum or peak water requirements of your crop. For winter crops the peak water requirement will usually be in spring when the crop is flowering. For summer crops it will usually be in the hottest period of the summer.

The amount of water a crop requires is dependent upon:

- Crop type and variety
- Yield goal – generally higher yielding crops will have higher water requirements
- Weather conditions (temperature, solar radiation, wind speed, humidity, rainfall)

For a particular crop and yield goal, the weather is the key factor. Crop water requirements are covered in more detail in WATERpak chapter 3.2 (cotton), WATERpak Section 4 (grains) and WATERpak chapter 5.5 (for CPLM systems).

System Capacity

For an irrigation system to work effectively it must have the capacity to supply water to the crop during the peak periods. 'System Capacity' is a measure of the ability of a system to meet these requirements. It is usually expressed as millimetres per day.

All irrigation systems should be designed to have a minimum capacity equal to the daily peak potential crop water requirement. If it is a multi-crop system, the design should be based on the crop with the highest peak water use. The 'Design' System Capacity is determined from two factors; the mean daily flow of water, and the irrigated area used in the design. It assumes the system can be operated 24 hours a day, 7 days a week in peak water use periods.

$$\text{System Capacity (mm/day)} = \frac{\text{Average daily pump flow rate (L/day)}}{\text{Area Irrigated (m}^2\text{)}}$$

Generally surface systems have ample system capacity and it is rarely a limitation to crop performance. This is because water is supplied in ample amounts at relatively infrequent intervals (e.g., 1 to 3 weeks). The limitation to having enough water available for the crop is the infiltration rate of the soil and the system should be designed to suit this. However, system capacity may be inadequate where water is being sourced from an irrigation scheme or trust where there is prescribed time or rate limitations for extraction, where water is being sourced directly from a low yielding bore, or where supply channel capacities are inadequate.

Pressurised systems have their capacity limited more commonly by the infrastructure; the capacity of the pump, the main supply lines and the field supply pipes. It is easier to end up with a pressurised system of insufficient capacity when compared with surface systems, because it is cheaper to buy and install lower capacity components in pressurised systems but the effect is not obvious until too late.

Insufficient system capacity means the crop may suffer yield and/or quality loss due to inadequate water availability. This may be apparent steadily over time or quite quickly.

Making changes to your irrigation system, such as increasing the irrigated area, diverting some supply flow to something else, or if the supply rate decreases for some reason, your System Capacity is lowered and the risk of suffering loss is increased.

In practice, the risk of crop losses is also increased because most irrigation systems cannot be reliably operated 24 hours a day, 7 days a week, and there are usually some losses of water between the supply point and the field. This is due to things such as:

- The availability and/or flow rate of supply water
- Leaks or seepage out of the system
- Runoff or movement of water off the field
- The number of hours per day that the system can be run
- Time required for shifting the system
- Labour availability and/or skill
- System down time for maintenance, break downs, etc.

These factors are taken into account to give what is termed the **Managed System Capacity** which is the effective or actual system capacity needed to match peak irrigation requirements. The Managed System Capacity is always lower than the

Design System Capacity, and it is this figure that should be equal to the peak crop water demand.

As application efficiency (E_a) takes account of water losses within a system, the managed system capacity can be determined by defining the proportion of system irrigation time as the Pumping Utilisation Ratio (PUR) and calculating thusly:

$$\text{Managed System Capacity (mm/day)} = \text{Design System Capacity (mm/day)} \times E_a (\%) \times \text{PUR} (\%)$$

As system capacity is a critical consideration for CPLM machines, further explanation is included in WATERpak Chapter 5.5.

Your decision of which system to select will be a balance between budget constraints and the level of risk that you are willing to accept. The key is to ensure that you don't simply opt for a cheaper quote and end up with an under-designed system; it is important to buy value, not cheapness.

Energy and labour requirements

With surface irrigation, little or no energy is required to distribute the water throughout the field, but some energy may be expended in bringing the water to the field, especially when pumped from groundwater. In some instances these energy costs may be substantial, particularly when application efficiency is low. Some energy cost will be incurred for land grading, preparation and field maintenance.

For pressurised systems, energy consumption is primarily determined by the operating pressure of the system, which varies considerably between systems. At the extremes, the Low Energy Precision Application (LEPA) emitters on lateral move and centre pivot systems may require only around 70 kPa (10 psi), while big-gun travelling systems may require 700 kPa (100 psi) or more. Other systems generally operate around 200 to 400 kPa (30 to 60 psi), depending on design of the sprinklers and the nozzles chosen.

Drip irrigation emitters require pressures ranging from 35 to 170 kPa (5 to 25 psi) but additional pressure is required to compensate for losses through the control gear (filters and control valves) and the pipe network. System pressures range from about 200 kPa (small systems on flat terrain) to 400 kPa (larger systems on undulating terrain).

Labour requirements for centre pivot, lateral move and drip systems are usually significantly less than other systems in terms of man-hours but these systems require more skills for efficient and reliable management.

Contour (or basin) irrigation involves the least labour of the surface methods, particularly if the system is automated. Border and furrow systems may also be automated to some degree to reduce labour requirements and pipe through the bank (PTB) systems have been used by some growers (WATERpak Chapter 5.3). The complicated "art" of border irrigation (and to a lesser extent furrow irrigation) requires skilled operators if high efficiencies are to be achieved. The setting of siphons or slide openings to obtain the desired flow rate is a required skill, but one that can be learned. The labour skill needed for setting border or furrow flows can be decreased by using higher cost equipment.

Selection of a system

Consideration of the factors above will narrow the options of irrigation systems to those suitable for you. Table 5.1.2 demonstrates the complexity that can be associated with selecting an irrigation system and is included to provide a quick reference guide to help with this process.

Once you have settled on your options, the next steps require more detailed investigation considering your own lifestyle and management preferences, management capability of the irrigation operators, labour requirements, financial and economic constraints, and how the irrigation system will integrate with operation of the rest of the farm.

It is worthwhile consulting an irrigation adviser to help with working through this process, and once you have made your selection, in order to have efficient system that will operate well for the long term, it is essential to engage a competent irrigation designer.

A calculator is available on the NSW DPI web site to help determine if a change of system is economically viable.

Table 5.1.2. Various factors to be considered when selecting irrigation systems

<table>
<tr><th></th><th>OWNERSHIP</th><th>WATER SUPPLY</th><th>DRAINAGE</th><th>WATER SALINITY</th><th>WATER SEDIMENT</th><th>MAX. SLOPE</th><th>WIND EFFECTS</th><th>CROP HEIGHT</th><th>PHYSICAL LIMITS</th><th>BLOCK SHAPE</th><th>SOIL TYPE</th><th>CROP TYPE</th><th>FROST CONTROL</th><th>LABOUR INPUT</th></tr>
<tr><td>PERMANENT SOLID SET</td><td>Owner operator</td><td rowspan="2">Less frequent, long application irrigation can be full cover</td><td rowspan="7">Minimal if irrigation system designed and managed correctly. Important for row crops planted on hills or beds.</td><td rowspan="4">Leaf burn possible with sensitive crops. Night time irrigations an alternative. LEPA may be used on CPLM to avoid foliage contact.</td><td rowspan="4">Minor filtration necessary only. Some nozzle types prone to wear.</td><td>Unlimited</td><td rowspan="2">Prone to poor distribution in windy conditions</td><td rowspan="2">Limited to riser height</td><td rowspan="2">No limit</td><td rowspan="2">Any</td><td rowspan="6">Heavy soils prone to runoff if application rate exceeds infiltration rate.</td><td>All crop types</td><td rowspan="2">Yes</td><td>Low</td></tr>
<tr><td>PORTABLE SOLID SET (HAND MOVE)</td><td rowspan="3">Well suited to leased situations as system can be readily moved</td><td>Unlimited</td><td rowspan="3">Highly suited to annual crops</td><td>Medium to high</td></tr>
<tr><td>CENTRE PIVOT</td><td rowspan="2">Frequent, short applications required due to high application rate</td><td>20%</td><td rowspan="2">Adequate with the use of drop tubes</td><td rowspan="2">Limited to span height</td><td rowspan="2">Must be clear of obstructions with path for towers</td><td>Circular (square or irregular possible)</td><td rowspan="2">No</td><td>Low</td></tr>
<tr><td>LATERAL MOVE</td><td>5%</td><td>Square or rectangular</td><td>Low to med</td></tr>
<tr><td>UNDER CANOPY SPRINKLER</td><td>Owner operator</td><td>Less frequent application needed as full cover irrigation is possible</td><td>Foliage contact can be avoided if angle of throw low enough</td><td>Reasonable filtration necessary. Plastic nozzles prone to wear.</td><td></td><td>Some, but less than solid set systems</td><td>Unlimited. Minimum canopy height of greater concern.</td><td rowspan="5">None</td><td rowspan="3">Any</td><td>Permanent plantings</td><td>Some</td><td>Low</td></tr>
<tr><td>SURFACE DRIP</td><td>Generally permanent for perennial plantings. Could be leased if above ground system.</td><td rowspan="2">Frequent water application needed as generally 1/3 of profile is wetted</td><td rowspan="2">Foliage contact avoided. Higher salt levels tolerated when well managed.</td><td rowspan="2">High degree of filtration necessary to avoid blockages</td><td rowspan="2">Unlimited. PC and ND emitters advisable.</td><td rowspan="4">Unaffected by wind</td><td rowspan="4">Unlimited</td><td rowspan="4">Perennial or annual crops</td><td rowspan="2">No</td><td>Low</td></tr>
<tr><td>SUB SURFACE DRIP</td><td>Owner operator</td><td>Heavier soils give better transverse movement.</td><td>Low</td></tr>
<tr><td>BORDER CHECK</td><td>Owner operator</td><td rowspan="2">Least frequent water application required</td><td rowspan="2">Drainage required. Re-use possible.</td><td rowspan="2">Foliage contact avoided. Water logging can reduce plant's salinity tolerance and damage soil structure</td><td>Filtration not needed</td><td>0.1% Landforming required</td><td rowspan="2">Square or rectangular preferred</td><td rowspan="2">Unsuitable for light soils due to excessive drainage. Clay soils with low infiltration rates are generally best.</td><td rowspan="2">Some</td><td>Medium</td></tr>
<tr><td>FURROW</td><td>Owner operator</td><td>Filtration not needed</td><td>0.1% Landforming required</td><td>High</td></tr>
</table>

Further information

FAO (2001) 'Irrigation Manual Planning, Development Monitoring and Evaluation of Irrigated Agriculture with Farmer Participation Volume III, Module 8: Sprinkler Irrigation Systems - Planning, Design, Operation and Maintenance' Harare, 2001

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Management' in association with the NSW Department of Land and Water Conservation, 2nd ed, Oxford University Press, Melbourne.

North, S. (2008) 'A review of Basin (Contour) Irrigation Systems I: Current design and management practices in the Southern Murray-Darling Basin, Australia' CRC for Irrigation Futures

NSW Department of Primary Industries (2008) 'Water Efficiency Technologies Module 2: Irrigation System Evaluation – Pressurised Systems Course Notes' NSW

Resources

Victoria DPI Irrigation System Selection and Design Guidelines

NCEA 'EconCalc' decision support tool used to economically evaluate the costs and benefits associated with a new irrigation system

5.2 Developing a surface irrigation system

Jim Purcell

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Key points

- what to consider when selecting an irrigation system
- what is involved in upgrading a surface irrigation system
- soil types for storages and canals
- the 'perfect' layout for an irrigation system

This topic is aimed at those wishing to develop a new surface irrigation system or expand or upgrade an existing system. It is designed to help prevent the farmer making the same mistakes that others have made over the last twenty years. It combines experience with commonsense and some detailed technical advice.

The development of a large-scale surface irrigation system can be quite complex and good advice is essential. It is often found that good advice is paid for one way or the other and it is cheaper before construction starts.

Questions for developments

A farmer looking to develop or upgrade any irrigation system needs to be able to answer all of these questions:

- Is the terrain irrigable?
- Are the soils fertile and suitable?
- Is the climate suitable for the crop?
- Is there a reliable, good quality water supply?
- How much area can be developed?
- How much will it cost?
- Will it make money?
- Do I have the required licences in place?

An irrigator must know the answer to all these questions before any construction proceeds.

What is irrigation?

Before looking at development in any detail it is worth reflecting on the basics. Irrigation is the process of artificially providing water to the soil in the crop root zone to enable a crop to prosper and yield well.

The process, then, includes the crop, the soil and the irrigation system.

These three aspects must work well together for a successful outcome. Poor performance from any one of these will lead to a poor result.

Matching irrigation system to soil

Lengthy and meaningful debates can be had on whether surface, sprinkler, or drip is the best form of irrigation. Of particular interest, however, is not which system may be preferred but **which system is best suited to a particular situation and crop**.

The single most important consideration in deciding which irrigation system is best suited to a particular situation is the **soil**.

The soil is the medium which takes in and stores the irrigation water for the crop to use. As stated above, the irrigation system, the soil and the crop must work well together to achieve a good crop yield.

Sandy soils: No matter how much a farmer may like surface irrigation, it is not possible to irrigate a field crop in a very sandy soil with surface irrigation because the water would infiltrate into the top part of the field mainly, and the tail end would get very little water. There are also real difficulties irrigating a crop in a sandy soil with subsurface drip because the water cannot sub up to the seed after planting. A sandy soil is well suited to efficient sprinkler irrigation.

Clays: Clay soils, however, are well suited to surface irrigation because the soil infiltration rates quickly slow to very low, allowing the water at the top of the field to flow over the wet soil and supply the dry soil further down the field.

Loams: A medium loam soil has more options, being basically suitable for all types of irrigation.

Matching the irrigation system type to the soil is a very important consideration which is sometimes overlooked. It is much easier to change an irrigation system than basic soil characteristics. Table 2.5.1 summarises the major considerations when selecting the most suitable type of irrigation.

Table 2.5.1. What type of irrigation suits me?

Irrigation type:	Surface	Mechanical sprinkler	Drip
Capital cost	L	M	H
Operation and maintenance	M	H	M–H
Labour requirements	H	M	L
Management	M–L	M	H
Water use	M–H	L–M	L
Yield potential	H	H	H
Surface drainage needs	H (regular laser levelling required)	M (for stormwater only)	M (for stormwater only)
Soil infiltration needs	M-H (high initial infiltration followed by moderate sealing for best distribution uniformity)	H (high infiltration rate required)	L.
Soils best suited	Heavy soils	Medium to light soils	Medium soils
Soils less suited	Sand (risk of deep drainage)	Heavy clays (infiltration problems)	Heavy (hard to pre-irrigate) Light (hard to sub up)
Lifestyle and personal	Your choice: some like dirt – some like gadgets.		

Note: L = low, M = medium, H = high

Answers for developments

A straightforward and systematic procedure has been developed to ensure that the correct answers are available at the outset and that nothing is missed. The following information must be obtained:

- preliminary inspection and selection of the potential area
- feasibility topographic (levels) survey of the whole potential area
- water quality analysis
- available water volume and reliability
- water supply delivery capacity
- determination of crop water requirements
- assessment of required irrigation water supply capacity
- agricultural soil suitability (samples and test pits – what's under the surface). See SOILpak B9 'Soil survey for development or re-development'.
- engineering soil properties for canals and embankment construction.

From this information it is possible to complete:

- a whole farm layout,
- a preliminary design and costing, and
- a preliminary economic analysis.

If the preliminary assessment is satisfactory, then it is possible to complete:

- a detailed survey and design,
- a final costing,
- a final economic analysis, and
- construction.

A thorough investigation is essential to ensure that any potential problems are foreseen and overcome before one clod of earth is turned. Development can stop at any of the above stages if serious problems are encountered. Once construction begins, it is very expensive to change, while it is easy and cheap to rub out and shift some lines on drawings. Shift things on paper, not in the field!

Using a consultant

As with all things, there are many who offer advice and are keen to help with irrigation development. There are those who 'know it all', although they have no formal training and little experience. There are those that know only a little but offer the lot. Be very careful. An irrigation consultant has a large impact on the development and it is vital that he/she is qualified and trained in the correct field, and is experienced. Ask if your consultant is qualified and what experience they have. Ask around and find out how they went with other projects.

Who can provide a complete answer to your development questions? A qualified engineer with detailed irrigation experience is a good option, as is a qualified surveyor with additional training in irrigation engineering. The important requirement is that an irrigation consultant must have the necessary training and experience in irrigation engineering to add value to an irrigator's own experience.

Any consultant may choose to use others qualified in specialised areas, such as soil science, but the consultant should know what has to be done and why, and should coordinate the project.

Development layouts

The first and most important part of the design process is to start with the whole farm layout. Worry about the detail such as sizes and so on after the whole farm is fitted together. Try a few alternatives and work with the designer and have your say (or at least review the preliminary layout before the detailed design is started).

A good layout requires:

- uniform runs of reasonable length
- regular field shapes
- a minimum number of control structures and crossings, and
- good access.

In particular, it means attention to detail and design. It should ensure that no unforeseen 'bugs' occur after implementation which reduce the efficiency of the operation.

It is vital that the layout is right before proceeding to the next steps. Any changes to the farm layout will mean changes throughout the whole system. It is quite expensive, for example, to decide later to merge two fields into one larger one, if land levelling has already put a pronounced step between the fields. If unable to afford required changes, a farmer may be stuck with an inbuilt inefficiency.

A good layout does not guarantee success, but at least it makes it possible.

A 'good' layout in fact could probably be defined as one that allows farmers to optimise their operations. This means that all of the elements that make up the system coordinate and function properly. Water is applied at the right time and in the right amount and uniformly, irrigation tailwater and stormwater run-off are removed quickly, cultural operations and access are enhanced, and labour is minimised.

Avoid having the supply and tailwater systems crossing. The best option is to have the supply system on one side of the development and the tailwater system on the other. Position the tailwater drain on the outside of the development to allow for easy overflow or blow-out of large stormwater events.

A staged development

Only a very few farmers can afford not to stage a development. Most tread the fine line of developing only enough to match finances but making this large enough to be an economic unit. As Stage I makes money, Stage II proceeds, and so on.

Any work done in Stage I must be readily adaptable for Stage II, III, and so on. Do not build temporary works for Stage I, rebuild for Stage II, and then build the final works for Stage III. For instance, build full-size canals and structures for Stage I, even though they are too big for the first area developed. If you need two pumps for the complete job, build the full pumping station and only install one pump for Stage I.

Design elements for development

Individual elements of the system must be selected and sized to be cost effective and efficient, and to fit into the overall system. There are many solutions to each design task, and several can be tested 'on paper' before the best is selected. Again, it is always cheaper to try pumps, shift earth and build canals on paper than in the field.

Do not forget to take stormwater and flooding into account when designing your system. In many cases it can be just as important to get the water off your fields during floods as it is to apply it.

Pumping station

The pump station is the workhorse of the irrigation system. Very large volumes of water are handled in an irrigation system, and the operation and energy costs makes it worthwhile optimising the pump and motor selection and the station layout.

Pump performance: When evaluating alternatives, consider operation and maintenance as well as capital cost. The cheapest pump to buy may not be the cheapest overall. Choose a pump which is efficient not just at the normal or most common flow and lift, but also over the full range of duties proposed (that is, normal river as well as low and high river). Allow a margin in the pump duties of up to 20% above the manufacturers' performance figures: the pump performance can be below the predicted performance by this margin because of pump wear and adjustment and a difference between laboratory and field conditions. Check several models and makes to find one which most closely matches the required duty. No one pump is going to be the best for all jobs.

Which motor?: Determine the input power required to the pump. This power must be made available from the motor continuously. The choice between diesel and electric motors can be made by considering capital, operation and maintenance costs together as a total cost. Other factors such as reliability of electricity supply and ease of operation must also be considered.

If diesel is selected, then the continuous power rating of the motor must be checked. The performance figures published by the engine manufacturers should comply with recognised standards. Unfortunately there are currently at least five recognised standards (ISO 3046, AS 4594, BS 5514, DIN 6270 and SAE J 816). The international (ISO) standard should be used if available.

De-ratings must be applied to this continuous power to allow for non-standard conditions, including altitude, air temperature, humidity and allowance for extras such as fans, alternators, and transmissions. As well as these specified de-ratings, allow a safety factor of 20%.

Final selection of the suitable motor will depend on the operating speed and power flexibility over the duty range. The most efficient motor is the one which operates closest to its point of minimum specific fuel consumption.

In the case of an electric motor, the continuous rating must be adequate to cover the pump duty plus a 15% safety factor.

Further information on pumps is available in WATERpak Chapter 1.8.

Station layout and dimensions: The most common reason for poor pump performance is a lack of adequate submergence of the pump inlet. A lack of sufficient submergence can result in poor performance and damage to the pump. In using an inclined river bank installation, one of the problems is finding a pool of sufficient depth. Depth should always be measured, and not taken from hearsay.

With vertical installations, the pump suction bell has to be located with the correct clearances from the walls and floor of the pumping station to ensure an evenly distributed inflow of water to the pump inlet. Uneven distribution and high velocities can favour the formation of vortices, introducing air into the pump and reducing capacity. The sump dimensions have to be sized to suit the pump capacity: don't use a rule of thumb.

The correct size of rising main or discharge pipe will be the lowest cost alternative when capital costs and operating costs are summed over the life of the pipe, using a suitable discount rate.

Consider head loss through the outlet when choosing between an overflow bubbler type and a flap gate:

- When pumping into a storage, an overflow type outlet may result in significant energy cost increases, unless a low level outlet is also provided.
- Be very careful with flap gates on pipelines as they can cause massive pressure surges in the pipeline from water hammer and can also cause damage to the pumping station structure when slamming shut.

Storages

An on-farm storage or ring tank can be used to harvest supplementary (off-allocation) stream flows and on-farm and overland flow (if appropriate). It also allows the easier management of regulated flows, as irrigation can start or finish before or after regulated flows arrive at the farm.

Storages should also be incorporated in the tailwater return system, allowing re-circulation of irrigation tailwater and capture of first flush stormwater, which may contain nutrients or pesticides.

Sometimes a 'surge reservoir' or 'buffer storage' is constructed to store stormwater run-off by gravity inflow for later pumping to the ring tank storage.

Siting: In planning the storage, consider using natural depressions for additional storage or using natural ridges for banks (where nature has constructed part of the embankment). Incorporating billabongs and gullies, however, is often of little advantage in many cases, as these features often store only a relatively small amount of water and are often subject to licence restrictions and environmental complications.

Sizing: Determining the best size of storage for a particular farm is difficult and should be done by simulating the storage behaviour under the anticipated crop demands, taking into account past stream flows. A computer program is available to do this laborious task.

The optimum depth to store this water is a balance between the cost of the embankment, the value of the land inundated, and the value of the water lost due to evaporation.

- For a given volume of water, a large shallow storage requires less earthworks but inundates a larger area and loses more water from evaporation.
- Increasing storage depth reduces land and evaporation losses, but the larger quantities of earth, longer construction hauls and the more rigorous construction requirements of higher banks rapidly increase costs.

A circular ring tank requires the least earthworks for a given surface area and can be used where suitable. More often a square or rectangular shape as close to square as possible is used to fit in with property and field boundaries.

Reducing evaporation: Evaporation losses can be reduced by constructing internal dividing walls to form cells. One cell is completely emptied at a time. Generally the value of the water saved cannot justify the cost of more than one dividing wall (two cells) with the appropriate connecting pipe work and gates. Celled construction often may suit staged development.

Protecting the bank: Large storages often suffer badly from bank erosion due to wind-generated waves. Rip rap and other hard surface protective measures cannot generally be justified economically.

Although grass has been used for bank protection in the past, this is no longer recommended as it has been found that even grass roots can penetrate many metres into a storage embankment and are thought to contribute to wall failures.

Flat inside batters are essential to allow dissipation of wave energy.

An 8:1 inside batter has been shown to be effective in minimising wave erosion.

Outside batters should not be constructed any steeper than 2:1 to provide stability and reduce rilling erosion from rain. Rilling erosion is also minimised by grading the crest to the inside. Detailed guidelines on storage design, construction, maintenance and management and included in the Guidelines for Ring Tank Storages.

Seepage: To build a costly storage without proper investigation is dangerous. Detailed soils investigation involving (at the least) backhoe pits and possibly electromagnetic (EM) surveys and pits is required to determine soil properties for design and to ensure, as far as possible, that any potential seepage paths can be cut off. It is worth having an engineer on hand to evaluate soils as they are dug from backhoe pits.

Skill and experience are also required to interpret EM surveys.

Supply canal

Where large flows are required and suitable clay soils are available, open canals are efficient and cheap. Before canals are constructed, the soils should be checked by test boring or backhoe pits. (Sealing of canals after construction is difficult and can exceed the initial canal cost.)

The canals should then be hydraulically designed, checking velocity and depth limits for stable flows, assuming uniform flow in most cases. Where possible, the slopes should closely follow the natural ground slopes to reduce excavation and padding, but velocities should be maintained between 0.15 and 0.5 metres per second to prevent weed problems and bed erosion. A freeboard on the banks above the normal water surface level should be incorporated to allow for bank settlement and flow depth variations due to canal conditions or discharge variations. Freeboards should increase with canal capacity from a minimum of 250 mm up to 500 mm or more.

Canal bends should have a sufficient radius to avoid erosion on the outside of the bends. A common rule is to use a radius of twenty times the water depth, or a minimum of 15 metres.

Head ditches

Head ditches normally have a slope of about 1 in 10,000 to minimise the number of control structures, to maintain uniform water levels above field level (command) and to make the setting of outlets (siphons) easier. Flat ditches have to be carefully maintained to ensure their capacity is not reduced. Steeper ditches require temporary or permanent checks to maintain head at the outlets. If fields are stepped to overcome steep side falls, the head ditch might require stepping at each field boundary. A flatter grade means a larger ditch to carry the same flow.

A low pad is normally constructed to the design grade with laser controlled equipment. The ditch can then be graded or delved to the desired depth, leaving the banks at the required height and on grade. The banks should be sufficiently high to provide a water level 150 to 300 millimetres above the field level, to provide adequate head for siphons or outlets.

The ditches are often designed with some over-capacity to allow for the effects of temporary weed growth and to accommodate flow variations. A flat-bottomed trapezoidal head ditch is more expensive to build than a 'V' ditch but has more capacity and is easier to use. An overflow should be provided at the end to allow non-damaging overtopping in an emergency.

Field design

The principle of surface irrigation revolves around the intake or infiltration rate of the soil. Water is provided to the field so that wetting of the root zone is satisfied by infiltration through the surface. Once the root zone at the top of the field is refilled, the water should advance down the field to continue refilling the root zone without wastage by continued high infiltration at the top. This process requires heavy clay or clay loam soils and reasonable field slopes to complete an irrigation in a reasonable time and to prevent the top end of the field from overtopping.

The appropriate run length can be determined in theory by balancing the advance and recession phase, giving all parts of the field approximately equal irrigation. Until recently, the infiltration characteristics of a field were difficult to measure and the field hydraulics difficult to model. Equipment and computer models are now available to optimise the run length to suit the soil and the farmer's requirements.

Ideally, the run length should be as long as possible, to enhance farming operations and limit the number of head ditches and taildrains and the labour in watering. Although longer runs have been used in the past, run lengths now are generally limited to a maximum of about 800 metres. In furrow irrigation, longer lengths require larger furrow streams, leading to furrows being overtopped and eroded. The possibility of furrow erosion from storm run-off is also a risk with long runs. Shorter run lengths are necessary in soils of higher infiltration capacity.

Other factors also impose limits on run length. In picking cotton, for instance, the capacity of the picker basket can limit the length. In many cases, the layout has to fit between two defined boundaries. The distance between boundaries should be divided by the whole number which gives a run length closest to the ideal. Once the run length has been selected, the furrow stream (number and size of siphons) and irrigation setting times are adjusted to evenly apply the required amount of water into the root zone.

Furrows should be designed to run down the slope, although some crossfall can be tolerated. Excessive crossfalls can result in furrow overtopping, leading to erosion across the furrows. Very little or no crossfalls can be tolerated with bay or border check irrigation. Uniform run lengths are desirable in any field and preferably on the whole farm. Furrows should be parallel to side boundaries, avoiding point rows at headland and taildrains.

Landforming is expensive, and it is not practical to change the natural slope too much. Large cuts can also result in the exposure of infertile subsoil, with subsequent yield loss for several years. On the other hand, it is difficult to achieve even gradings where slopes are too flat, say 1:2000. If necessary, shorter run lengths can be used to minimise earthworks on very flat country.

Nearly all fields are now graded using laser controlled equipment. Lasers make construction easier and provide very uniform grades which greatly facilitate irrigation and drainage. Computer programs are available to calculate grading schedules. Fields should be broken into sub-areas to minimise earthworks, and different combinations of run length, down slope and cross slope should be tried.

Be wary of designers and contractors who are overnight experts. Just because they have a computer doesn't mean that they can design a system: 'have computer, can design' or 'have laser bucket, can construct' does not make sense. Training and experience will save large sums of money with field design and construction. To start laser grading a field without a design is like driving to Birdsville without a map.

Taildrains

Taildrains are required to remove furrow or bay run-off following irrigation or rainfall. In most areas, drain capacity will be dictated by storm flows. The capacity provided will depend on the time in which drainage must be provided. Most crops require drainage of stormwater within 24 to 48 hours. For high value, waterlogging-sensitive crops such as cotton, more rapid drainage is desirable, but the costs of drains and culverts increase rapidly. The design capacity is therefore a compromise between the time taken to drain the field and drainage costs.

The selection of the design storm is necessary to complete the hydraulic design of the system. The cost of providing facilities to cater for a large event may never be recouped. A one in five year event is usually selected as the design storm for cotton. The drain capacity is then designed to remove this water from the field in, say, 24 hours.

Taildrains should have gentle grades, but preferably steeper than 1:3300, with almost zero capacity at the end. Drain batters should be very flat to allow ready access across the drain when it is dry and provide a turning area for cultivation practices. Generally a 20 horizontal to 1 vertical slope is used on the field side with say 10:1 batter on the road side. Taildrains must be low enough to completely drain the field without causing erosion into the drain from the irrigation furrows or bays. Generally the depth between the drain bed and the field level should not exceed 300 mm to 400 mm.

Tailwater return system

Scarcity of water and environmental factors mean that re-circulation of tailwater is essential in most areas. The high cost of labour also means that careful supervision of irrigation, cutting off of siphons at precisely the correct time, is often not practical. Re-circulation is an economic alternative.

If possible, tailwater should be collected in a buffer storage to overcome the problem of matching tailwater pumps to the variable tailwater flows. When sufficient volume has collected in the buffer, the water can be pumped to a main storage or directly to the supply system for irrigation. Pumping tailwater directly back into the supply system for irrigation can cause problems with adjusting the necessary control structures to cater for the variable tailwater flow.

The tailwater return system also collects stormwater run-off, which in many areas is a welcome addition to the water supply. Even with buffer storage, there is a need to safely dispose or blow-out stormwater from large events. Tailwater pumps cannot keep up to a large storm or may not be working during a storm, due to access problems, for example. An emergency overflow facility is required, allowing excess water to be disposed of safely. A grassed bywash around the buffer storage may be used, or a gap can be provided in the bank of the tailwater return drain where design water level is at natural surface level. A gated weir structure in the tailwater system is sometimes required to release stormwater but exclude floodwater.

Culverts

All surface irrigation systems require culverts for access and flow control. Culverts are expensive, and a good layout will minimise the number required. Concrete culverts have a longer life, but steel pipe is easier to lay and can be cheap if second-hand pipe is available. Modern surface coatings are now increasing the service life of steel structures.

The choice of correct culvert size is a compromise between the capital cost of the extra size versus the capital and operating cost due to extra head produced by using a smaller pipe. The smaller pipe will require a greater head (water level upstream of the culvert will rise), requiring higher canal banks upstream and resulting in higher pumping costs over the life of the project.

Headwalls should be used to:

- contain the road or canal embankment,
- make the culverts more efficient hydraulically (reducing head loss),
- minimise silting in the culvert, and
- aid maintenance.

Headwalls can sometimes be added in the final stages of the development to save initial cost.

Remote sensing

The technology of remote sensing of water levels in channels and storages and remote control of gates and pumps is becoming very useful. It can provide significant advantages during normal irrigation and when controlling stormwater. The possibilities are nearly limitless:

- alarms can be set when water reaches a certain level anywhere on your farm;
- pumps can be started and monitored;
- gates can be opened and closed from the office or anywhere else to reduce the need to drive on slippery and narrow channel banks.

Remote sensing also provides the opportunity to collect accurate information for the assessment of on-farm water use efficiency and system performance. In the near future, accurate on-farm water balance measurements will be routine. With this technology it will be possible to know where each megalitre is on the farm.

Soils for storages and canals

Soils can loosely be classified by particle size as follows:

Class	Particle size
Rock	Large
Gravel	
Coarse sand	
Fine sand	
Silt	
Clay	Very small

Generally, as the particle size of the soil becomes smaller, the soil leaks less water. For water-holding and conveyance structures, only silts and clays are suitable. Sands and gravels in a ring tank storage or supply canal or drain will leak too much water. This leakage will also continue indefinitely unless sealed by membranes or clays.

A clay is made up of particles which are microscopic in size and are held together by molecular forces. Once wet a clay will leak only a very small amount. Very heavy clays have a saturated permeability which is so small it is difficult to measure.

Silts are made up of particle sizes which are very small (cannot be seen with the naked eye) but which are considerably larger than clay particles. Silt does leak a little and will continue to leak even when saturated.

Ideally then, all ring tank storages and earthen canals and drains should be constructed out of clay. Once the floor and walls of a clay ring tank or canal become wet the seepage losses are very small.

Any silts, sands or gravelly areas within the ring tank or canal will leak and must be sealed by lining with a layer of compacted natural clay from nearby or by membranes or imported bentonite or similar.

Experience and training is required to distinguish between a silt and a clay because both look very similar, particularly when dry.

Further information on storage and canal seepage is available in WATERpak Chapter 1.6.

Electromagnetic surveying for storage or channel site selection

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Irrigation infrastructure can experience significant seepage losses if inappropriately located on permeable soils. Detailed soils investigation involving backhoe pits are required as a minimum to determine soil properties for storage design. (See, for example, *SOILpak for cotton growers* C1 'Soil pit digging: where, how and when?')

A better option (one which provides more detail) is an electromagnetic (EM) induction survey. EM surveys of existing or planned irrigation infrastructure and irrigated fields can show variations in soil properties. The site selection of channels and on-farm storages has been improved by the use of EM surveys. These surveys allow the delineation of a field into distinctly different areas, based on apparent electrical conductivity, and allow accurate targeting of soil sampling and measurements. The appropriate location of channels and on-farm storages reduces losses to groundwater systems and increases the water resource available for productive use.

EM surveys generate data in the form of apparent electrical conductivity (EC_a). Apparent electrical conductivity is primarily related to the salt, clay and moisture content of the soil. The EC_a value is a potential indicator of soil permeability. The EC_a data are linked to GPS data at the time of collection: this ties them to a specific location for future reference. The resulting point source data are analysed with the aid of computer-generated mapping to look for trends. Several sites in each test area are then selected for 'ground-truthing' by backhoe pits or test boring and higher level analysis. The aim of ground-truthing is to confirm the range and properties of soil variations identified by the EM survey.

Soil profiles can be highly variable, consisting of layers of fine, medium and coarse textured soils, which resulted from prior stream and aeolian deposition that formed the current landscape. Surface soil features do not necessarily give an accurate indication of the nature and permeability of the underlying soil. Most soil based irrigation structures require 3.5 to 5 m of uniform medium to heavy clays below the deepest cut in order to have acceptable seepage losses.

The EM technology allows for a much more thorough subsurface investigation. It also allows for identification of patterns of soil types.

Further information on EM surveys is included in WATERpak Chapter 2.6.

The perfect layout

Naturally, there is probably no such thing. Obviously the 'perfect' layout for Narrabri, NSW will be different to that for Emerald, Queensland and Hay, NSW.

However, there are a number of desirable qualities a good layout should provide:

- uniform run lengths over the whole farm
- regular rectangular fields
- a minimum number of control and access structures consistent with easy access
- a deep square ring tank to store irrigation tailwater and first flush stormwater and to help manage regulated water
- a supply system on one side of the farm and a tailwater return system on the other side, with drains less than 3 m deep and canals with banks less than 3 m high
- a tailwater return system on the outside of the irrigation area to allow for stormwater blow-out
- a natural depression at the bottom of the tailwater return system which can be used as a buffer storage filled by gravity during large storms; its contents can then be pumped back to the ring tank or fields at leisure
- each field with the same soil type within the field.

What is the **optimum run length**? Like everything else with an irrigation system, this depends on the crop and the soil and the natural slopes. The objective of selecting a run length is to provide the longest run that allows even application of irrigation water and that applies the required depth of water in a convenient irrigation setting time without erosion of the soil during irrigation or storms.

As the run lengths increase the furrow flows need to become larger and the tailwater volumes become larger to achieve even irrigation. Further, with longer run lengths it becomes very difficult to apply small irrigation applications. In summary, shorter is better for irrigation efficiency and uniformity of application but the cost of development and operation increases. The best compromise for cotton grown on grey cracking soils is between 400 and 800 metres.

The optimum grades? This answer is simple: as close to the natural slopes as possible, because changing grades is very expensive and damages the thin productive topsoil layer. Anything from 1:500 (0.2%) to 1:1650 (0.06%) can be managed efficiently by varying furrow flows and irrigation setting times. Grades steeper than 1:500 can suffer erosion from storms if runs are too long, and grades flatter than 1:1650 are difficult to drain and yield loss from waterlogging can be a problem.

Conclusion

It is possible to 'put together' a surface irrigation system with little more than some earthmoving equipment and commonsense. Many farmers are prepared to do this, unaware of the complexities of the system with which they are about to become involved (ask someone who has tried!). The result is very often a system that costs more to construct and is a pain to operate. This may be in the short term, due to higher or unnecessary construction costs and loss of their time, or in the long term, due to higher operating costs.

An irrigation engineer can marry the skills of a civil or agricultural engineer and an agronomist. He or she should ensure that the system is cost effective and that it can be operated efficiently. Design costs generally run to only a few percent of the overall development costs.

Every element of a surface irrigation system can and should be designed to operate correctly. It is a great relief to a farmer to know that what is being built will work properly. A good design repays itself many times over.

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5.3 Surface irrigation performance and operation

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Key points

- Efficient surface irrigation requires management and maintenance of all system components between the head ditch and the tail drain.
- Irrigation performance is controlled by a number of variables which influence performance to differing degrees.
- Efficient irrigation involves careful management of these variables and an understanding of how they interact.
- Evaluating the performance of a surface irrigation system can be complex, but is essential to improve efficiency.
- Some practices used to improve performance must be managed precisely otherwise performance may actually be reduced.

Surface irrigation is the process of applying irrigation water to the field surface and using the field itself to distribute the water. Common forms of surface irrigation include furrow irrigation, where water flows down narrow furrows between crop rows, or border-check irrigation, where water flows down strips of the field that may be up to 100m wide. Systems such as bankless channel can be more challenging to evaluate because the water is applied from the bottom of the slope, making the surface hydraulics more complex. Further information on bankless channel irrigation is included in WATERpak Chapter 5.4.

Surface Irrigation methods, particularly furrow irrigation, are commonly utilised throughout the Northern Cotton and Grain growing regions of Australia. This application system is often viewed as being reasonably low cost and simple to manage, although some erroneously often consider the performance to be reasonably poor.

In reality, furrow irrigation systems can sometimes be quite capital intensive, and a high labour requirement can often result in reasonably high operating costs. Perhaps most importantly, the performance of surface irrigation systems can be very high, rivalling drip and CPLM systems with the right management.

However obtaining the optimal performance of a surface irrigation system can be a challenging management task and this chapter aims to give a better understanding of the process.

Furrow irrigation system components

Head ditch

The purpose of a head ditch is to consistently deliver sufficient water at an appropriate head. The aim is to achieve a steady flow rate onto the field. Maintaining a constant flow rate requires specific management and maintenance. Management involves regulating flows in the system and selecting and operating outlets appropriately, while also maintaining adequate freeboard. Regular maintenance such as desilting, weed control and removal of obstructions must also be done.

Head ditch flow is regulated at the source, while head ditch levels are determined by downstream control structures. Water level should be kept as constant as possible while irrigating, as fluctuations cause the outlet discharge to change. Consequently, to maintain a constant head, discharge from all outlets should equal the head ditch inflow. A minimum 0.15 m freeboard should be maintained in the head ditch.

Because soils other than heavy clays are more susceptible to erosion, head ditches in these soils should be designed to keep water velocity below 0.6 metres per second (m/s). Heavy clays should be limited to flows below 1 m/s. A velocity above this may cause scouring. Velocity should also be kept above 0.15 m/s, or silting may occur.

Measurement of flow in head ditches is quite complex and is typically achieved using ultrasonic flowmeters (for example, Doppler meters: see WATERpak Chapter 1.7.) or by measuring depth through calibrated control structures such as flumes or weirs. It may be possible in some circumstances to measure flow over irrigation checks, whilst modern channel gates often incorporate measurement technology.

Obstructions in the head ditch can cause scouring and increase the system head loss. While head ditches less than 1 metre wide or less than 0.2 m deep are most susceptible, obstructions in all head ditches should be avoided. Obstructions can be caused by silting, weeds and embankment slumps.

Siphon and culvert hydraulics

Water movement requires energy. Overcoming the resistance or friction as water moves through channels or pipes accounts for most of this energy use. The energy driving a system is called 'head' and the loss in energy is called 'head loss'. Careful design and management of a system can reduce the head loss of a system. Irrigation systems are usually designed and operated to limit the total system head loss, which usually minimises energy costs, channel and pipe sizes, and prevents the overtopping of channels.

Head loss occurs whenever water flows. It increases when water goes from a broad slow flowing channel into a fast-flowing pipe. Bends, restrictions and sudden changes in channel size or pipe diameter all increase head loss.

In surface irrigation systems, head loss is evident as a drop in water level from upstream to downstream. This means it can be measured reasonably across any structure, such as through-the-bank pipes, culverts or checks.

Understanding the interaction of head and flow rates is important for correct application of water onto a field. Flow through siphons and culverts increases as head increases, and decreases as head decreases. It is important to install culverts so they run at their full capacity, as culverts running partially full have greater head loss and restrict flow.

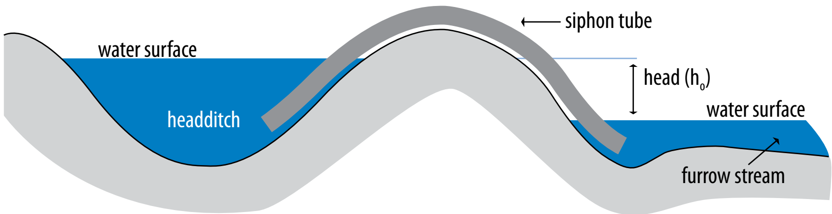
This is an important and seemingly counter-intuitive concept which means that culverts should be placed at sufficient depth so as to operate with full flow. For example, culverts used to drain a field should be placed with the top inside level of the culvert set equal to the lowest level of the field.

Siphons

Siphons can operate under two situations: submerged flow and free flow conditions (Figures 5.3.1 and 5.3.2).

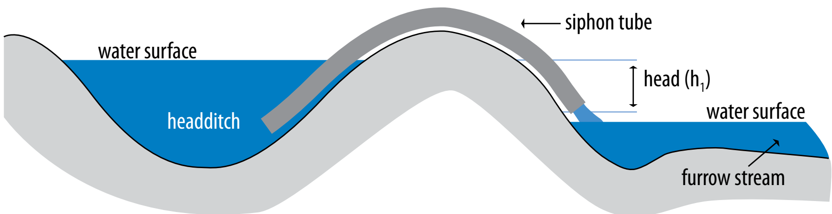
- When operating under submerged flow conditions, the available head is the difference between the upstream water level and the downstream water level.
- Under free flow conditions the head is the difference between the upstream water level and the level of the siphon outlet.

Figure 5.3.1. Siphon operating with submerged flow



Source: J Purcell

Figure 5.3.2. Siphon operating with free flow



Source: J Purcell

In most cases, with typical irrigation head ditch layouts, siphons will be operating with submerged flow (Figure 5.3.1). Under these conditions, siphon flow rates can be affected by water level in the furrow stream and the head ditch, siphon length and diameter, and the internal roughness of the siphon. In one trial, variations ranging from 27% to 152% of the mean siphon flow rate occurred as a result of these variables. This has obvious implications for the distribution uniformity of a given field.

Pipe diameter has a significant influence on siphon capacity. Siphon flow rates can be measured using methods outlined later in this chapter.

Siphon placement can affect flow rate. Placement of siphons at different angles to the flow of the head ditch causes a preferential flow into some of the siphons that results in flow variation. Placing all siphons perpendicular to the head ditch can help overcome this problem.

Any variation in cross-sectional area will affect flow rate. Walking on siphons or accidentally pushing them into the ground when starting them may cause kinks, reducing their cross-sectional area. Extreme heat may cause them to become oval, also reducing the cross-sectional area.

Also note that siphons are available in both metric and imperial sizes. Although these siphons may look to be a similar size, their internal diameter varies which will result in different flow rates (also see here).

For example two inch and 50 mm siphons can be easily confused, but flow can vary by up to 27%. For one example in the referred article, this resulted in an additional application of 0.37 ML/ha in only one irrigation. Also note that different manufacturers produce different wall thickness pipe which also results in small differences even within the same size classification.

Theoretical flow rates for a range of siphon sizes are presented in WATERpak Appendix 1.

Pipes through the bank

Pipes through the bank (PTBs) operate like conventional culverts and may be either inlet- or outlet-controlled depending on the water level in the head ditch and the irrigation field as well as the pipe geometry. The relationship between head and pipe size on the theoretical flow of PTBs again demonstrates the importance of pipe diameter and amount of head (Table 5.3.1).

PTBs are different to most other culverts on an irrigation farm. Flow rates in PTBs are often controlled from the inlet. As a result, changes in supply level can have significant effects on PTB flow rates. Preferential flow down some furrows, caused by wheel tracks and trash build-up, and maintaining adequate head are two problems often encountered with PTBs.

A recent case study of successful PTB application can be found on page 29 of the Australian Cotton Water Story and a video is also available. The case study includes a number of design considerations and is highly recommended for those with an interest in PTB systems

Table 5.3.1 Theoretical flow (L/sec) for pipes through-the-bank (PTBs)

	Pipe diameter (mm)					
Head (mm)	**150**	**200**	**225**	**300**	**380**	**450**
100	16	29	38	70	114	162
150	19	36	46	85	140	199
200	22	42	54	99	162	229
250	25	46	60	110	181	256
300	27	51	66	121	198	281

Note: Inlet controlled flow

Furrows

Furrow and bed dimensions can assist in improving water use efficiency and crop health on farm. Cotton has traditionally been grown on 1 metre beds, however there are a number of alternative bed configurations being used to achieve a variety of outcomes to suit local conditions and soil types.

While weed control in furrows is important, the presence of stubble or a root mat on bed edges can reduce the incidence of erosion while creating biopores (holes created by roots and soil organisms) that improve infiltration.

Deep furrows may promote adequate drainage of the field. However, deeper furrows mean steeper bed edges, which are difficult to maintain and be prone to slumping. Slumping encourages erosion and may dam furrows, resulting in waterlogging of the bed. More information on furrow design can be found in SOILpak D1.

Reduced in-crop cultivations in Roundup® Ready cotton sometimes results in hill slumping. Cultivation reforms hills, helping to prevent slumping and subsequent damming of furrows. Blocking off a furrow leads to poorer DU. Where two or more rows are irrigated using one siphon, preferential flow into one furrow may result, leading to poor DU. Slumping or silt build-up in one furrow can also cause preferential flow.

Waterlogging can result in dramatic production losses (see WATERpak Chapter 3.4). This should be considered on very flat fields (flatter than 1:1500) both from an irrigation perspective and a rainfall drainage perspective. Furrow lengths that are too long may result in excessive deep drainage and waterlogging at the top end of the field. This is because the infiltration opportunity time is too long.

Fields are laser graded to a certain slope for good drainage and high DU. Fill areas and gilgai country suffer slumping over time. Fields should be re-laser-graded or polished as required to ensure a high DU is maintained. Steep slopes or application rates that are too great can result in furrow water velocities that may cause erosion of the furrow and siltation problems elsewhere.

Fields with point rows (non-square fields) need to be carefully managed. The varying furrow lengths will require different irrigation times to avoid waterlogging. This has a greater labour requirement as siphons will need to be cut at different times but a high DU can be maintained. A different approach is to reduce the siphon sizes on the shorter rows to slow the flow rate. This may be appropriate, however remember that the aim in these sections of the field is to have an infiltration opportunity time equal to that of any point in the remainder of the field. These furrows do not necessarily need to come out at the same time as longer furrows provided the infiltration opportunity time is managed correctly.

Tail drain

Tail drains remove run-off from the field created by both irrigation and rainfall events. Tail drains are typically designed to drain run-off generated by a one-in-five-year, 24 hour storm event. Rapid removal is necessary to prevent in-field waterlogging and reduce the yield penalty created by waterlogging (see WATERpack Chapter 3.4).

In order to correctly design tail drains, stormwater run-off needs to be estimated. Climatic factors, current soil moisture content and the size of the field will influence the total run-off. It must be appreciated that designing tail drains is site specific with many factors to consider. Tail drains should be constructed with a minimum gradient of 1:3000. Drain capacity should increase from the beginning of the drain with maximum capacity at the end of the tail drain. Batters should be shallow, 10:1 on field side to minimise erosion and 5:1 on road side to allow machinery access. Drains should be sufficiently deep to prevent water backing up into the field, yet sufficiently shallow to prevent erosion occurring between the furrow and the drain. Generally the depth between the furrow and the tail drain should not exceed 250 mm. There is a compromise between the cost of constructing large tail drains to cope with rare storm events against the penalty of suffering yield losses associated with water backing up onto field due to smaller tail drains.

Tail drains should drain into the tailwater return system with a minimum depth of 700 mm between the furrow level and the drainage return system. This will ensure complete drainage of the field is achieved, minimising waterlogging. It is important that the tailwater return system and pump are designed to cope with the large volumes of water storms can generate. Construction of surge areas is an option to minimise drain and pump sizes and allow settling of sediment. The water in the surge area can then be pumped once the immediate storm water is removed.

As in head ditches, water velocity in the tail drain should be kept below 0.6 m/s in soils other than heavy clays, which should be limited to flows below 1 m/s. Flows above these velocities can cause scouring. In contrast, flows should be kept above 0.15 m/s or excessive silting may occur.

Culverts should be adequately sized to cope with drainage requirements and high trash loads. High volumes of trash in undersized culverts may lead to blockages and result in field waterlogging problems caused by backed up water. Blockages can also lead to scouring and significant head loss. Some design considerations for trash management include:

- Install drainage culvert upstream of the channel end to allow trash accumulation at the end of the channel while preventing culvert blockage.
- Enlarged culverts allow trash to be carried through rather than causing blockages.
- Ensure regular maintenance is carried out to limit blockages.

Surface Irrigation Hydraulics

Unlike any other irrigation system, the application of water in a surface irrigation system is influenced greatly by the soil properties, as it is the soil which acts as the water distribution method.

Water application to a field, as either irrigation or rainfall, typically results in a combination of five processes.

1. Useful water is applied to the root zone, which may continue until the soil profile is filled to field capacity.
2. Additional water applied to the root zone, may increase the soil profile to saturation and cause waterlogging (WATERpak Chapter 3.4).
3. Excess water infiltrates through the soil profile, leaving the root zone as deep drainage (WATERpak Chapters 1.4 and 1.5). (This process may continue after application ceases, as the saturated soil drains to field capacity).
4. Excess water leaves the field as runoff (tailwater).
5. Water is used through evapotranspiration (WATERpak Chapter 2.8).

An ideal system will satisfy the first condition and provide for the fifth condition, whilst minimising the extent of the remaining three.

Infiltration

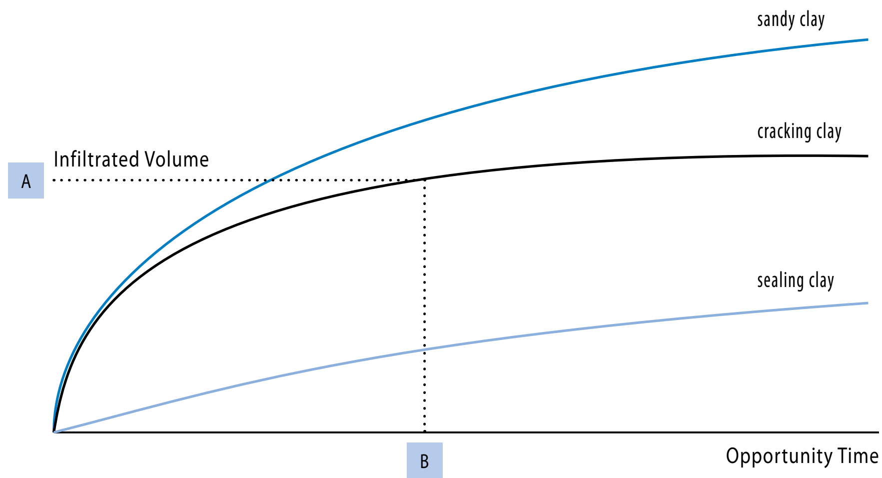
The entry of water into the soil is governed by the **infiltration characteristic** of that soil. The infiltration characteristics of different soils can vary considerably.

- Open sandy soils may allow a rapid intake of water which does not diminish markedly over time.
- Many cracking clay soils have a very rapid initial infiltration rate, which decreases over time as the soil swells and the pore space closes up.
- Hard setting soils may have a low initial infiltration rate which also does not vary considerably over time.

The infiltration characteristic can be represented by a cumulative infiltration curve. A **cumulative infiltration curve** shows the total amount of water that can infiltrate into a soil over a given period of time. Figure 5.3.3 is an example of some cumulative infiltration curves.

Note that the soils in the figure do not represent the whole range of infiltration characteristics that may be experienced. Similarly, an infiltration characteristic for a single soil may actually change between seasons or even within a season.

Figure 5.3.3. A range of cumulative infiltration curves showing different soil infiltration characteristics. (Source – P Dalton, NCEA)



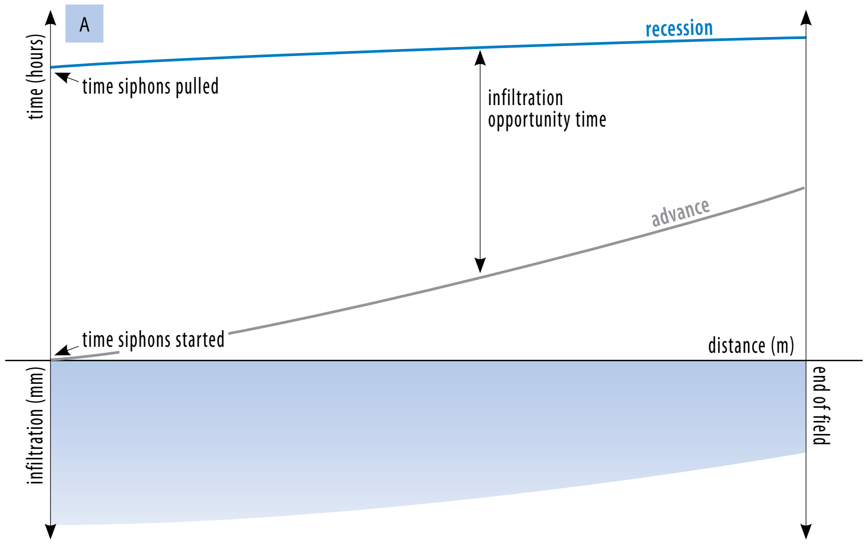
Opportunity Time

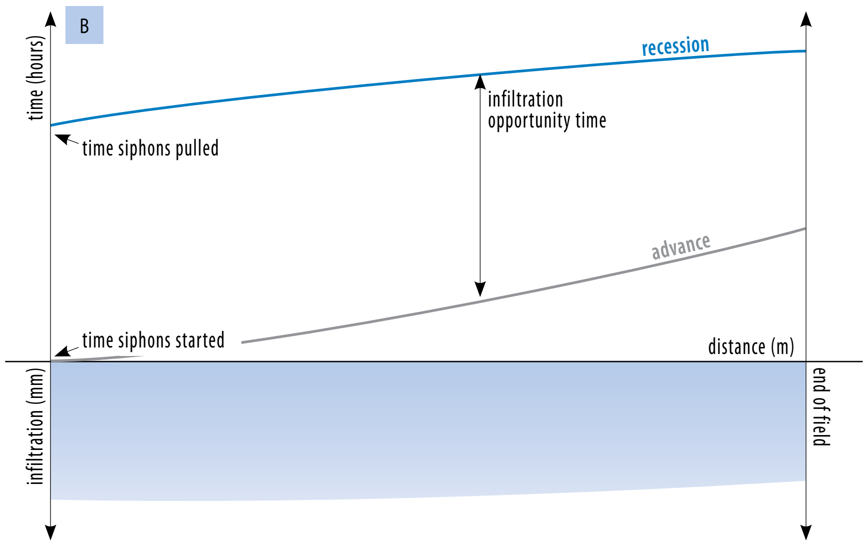
The infiltration opportunity time is the length of time that water is present on the soil surface for infiltration to take place. To achieve the best performance, the opportunity time for an irrigation should equal the amount of time necessary to apply the required depth of water. In Figure 5.3.3, if the amount of water required is indicated by 'A', then the time required to apply that amount of water is indicated by 'B'.

The opportunity time for a furrow irrigation event often varies along the furrow. This is because the length of time that the water is present on the surface of the soil at any location is the difference between the time the water arrives (**advance**) and the time the water leaves (**recession**). As illustrated in Figure 5.3.4, the rate at which the water advances down the field is different to the rate at which it recedes.

Even infiltration is achieved when the advance and recession rates are similar, resulting in an opportunity time which is more even along the entire furrow length.

Figure 5.3.4. (a) Opportunity time varies with distance down the field (b) More even infiltration results from advance and recession curves which are similar.





Distribution Uniformity

Distribution uniformity, which has been previously discussed in WATERpak Chapter 1.2, is a measure of how evenly water has been applied and is expressed as a percentage (%). Low distribution uniformity is caused by an uneven opportunity time along the length of the furrow. The result is either part of a field being under-watered or part being over-watered, in an attempt to apply sufficient water to the rest of the field. It is this practice that most often causes waterlogging to significant parts of a field, which in turn results in potential yield loss. Calculating distribution uniformity for furrow-irrigated fields typically requires computer modelling to simulate an irrigation event.

$$\text{Distribution Uniformity (DU)} = \frac{\text{Average of smallest 25\% of infiltrated amounts}}{\text{Average of all infiltrated amounts}}$$

In addition to the variation in uniformity along the length of a furrow due to differences in infiltration opportunity time, infiltration may vary between furrows across the width of a field. For example, greater compaction in wheel tracks decreases infiltration compared with non-wheel track furrows. Similarly, head may vary along the length of a head ditch, resulting in different inflow rates to furrows in different parts of a field.

Irrigation duration may also vary, particularly between different siphon sets, and this variation is often correlated to the time of day that sets are started. When evaluating distribution uniformity of a furrow or group of furrows, it is important to understand how representative these furrows are of the remainder of the field.

Application Efficiency

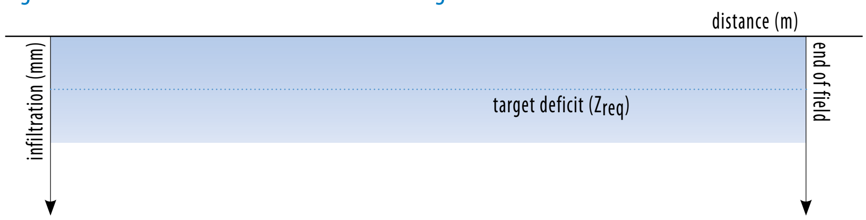
Application efficiency, also previously discussed in WATERpak Chapter 1.2, relates the amount of water applied in an irrigation to the amount of water available to the crop for use and is expressed as a percentage. A high efficiency means that most of the water applied has remained in the root zone available for plant use.

$$E_a = \frac{\text{Irrigation water available to crop}}{\text{Water received at field inlet}}$$

A uniform irrigation does not guarantee efficiency and an efficient irrigation does not guarantee uniformity.

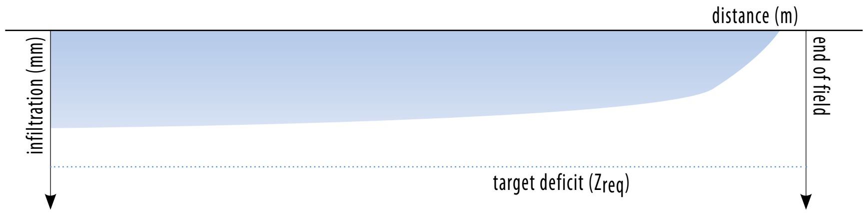
For example, an irrigation may be almost perfectly uniform, in that the same amount of water is applied to every part of a field. However if the total amount of water applied were twice that required, the application efficiency would only be 50% (Figure 5.3.5).

Figure 5.3.5. A Uniform but inefficient irrigation.



In contrast, an irrigation may be perfectly efficient, such that all of the water applied to the field remains in the root zone available for use. However if this water only made it across half of the field, the uniformity will be extremely low (Figure 5.3.6).

Figure 5.3.6. A non-uniform but efficient irrigation



Hence optimum system performance is achieved when both application efficiency and distribution uniformity are high.

Requirement Efficiency

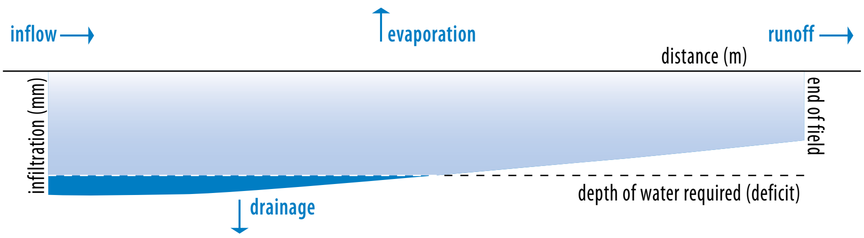
One other term that may be used to describe the performance of an irrigation system is requirement efficiency. The requirement efficiency simply refers to how well the irrigation event satisfied the soil moisture deficit at the time of irrigation.

If any part of a field is under-irrigated, the requirement efficiency will drop below 100%. However, the closer the requirement efficiency is to 100%, the greater the chance that the application efficiency will be reduced, as water will inevitably be lost as drainage or runoff.

A requirement efficiency of less than 100% is perfectly acceptable, especially if the distribution uniformity is high. This simply means that the soil moisture deficit has not been completely refilled, and the timing of the next irrigation should reflect this.

Figure 5.3.7 demonstrates the components of an irrigation event. Potential water losses are represented by the evaporation, drainage and runoff arrows. The volume of water that is applied to the root zone is indicated by the light blue coloured area.

Figure 5.3.7. Representation of a furrow irrigation event



Evaluating Surface Irrigation Performance

The theory behind these surface irrigation processes is actually reasonably straightforward. However, most of the action is happening below the soil surface. This makes many of the variables virtually impossible to measure. Perhaps the most important variable used for evaluating performance is the volume of water represented by the blue region in Figure 5.3.7. But how can you physically measure this volume? You would need to measure the volume of water that has infiltrated the soil vertically, at every location down the length of the field!

These parameters can be determined by making some much simpler measurements and then modelling the irrigation event. This process is offered commercially as the Irrimate™ service. It is also possible to take some basic measurements by hand to determine information such as water use indices and the volume of water applied.

Basic measurements and benchmarks

There are a number of measurements that can be taken with relative ease that are important for making tactical irrigation management decisions and to calculate water use indices (see WATERpak Chapter 1.2) that can be used to broadly benchmark performance.

Measurement of applied and runoff water volume is perhaps the most critical piece of water information that can be collected for a surface irrigated field, although practical issues often mean that accurate measurements are difficult to obtain. This is especially the case for tailwater, which can be very difficult to measure without specialised equipment. The most practical method is to measure the amount of tailwater that is recycled using a storage meter (see WATERpak Chapter 1.6) or a flow meter on the pump used to return tailwater to the storage. However tailwater re-lifted into storages is usually a combination of runoff from a number of fields, which makes individual field analysis difficult.

In contrast, measurement of water applied to a field can generally be achieved in two ways. The first method involves measurement of bulk flows; that is, the total water delivered to a field. This can be achieved by installing a meter on a supply point to a field, which may be a pump, bore, culvert or other similar structure. Measurement can be complicated where more than one field is irrigated by a particular water source at any one time, as it can become expensive to install separate meters for each field. On the other hand, the usefulness and accuracy of data will be compromised if fields are grouped together in order to reduce the number of measuring points as the performance of individual fields can vary greatly. It may be possible to minimise physical metering by using WaterTrack™ to model water flows around the farm. When used in conjunction with storage meters and carefully selected metering points, this tool can be calibrated to accurately reflect on farm water movements. Further information on WaterTrack™ is available in WATERpak Chapters 1.2 and 2.3.

Figure 5.3.8. One of the commercially available water flow meters capable of measuring bulk flows onto and off an individual field

The second measurement method involves measuring flow for a selection of individual furrows or bays and then extrapolating that data across the field. By measuring a selection of furrows located at points across the field, this method also provides a good indication of the potential differences in flow rate that may occur within individual fields and is extremely useful for managing irrigation events. Simple techniques for measuring water flow from a single siphon include using a bucket and stopwatch (Figure 5.3.9) or by measuring head height (Figure 5.3.10) and relating this to flow using a siphon head-discharge chart (see Appendix 1).

Figure 5.3.9. Using a stopwatch and bucket to calculate siphon flow rate

To measure flow using a bucket and stopwatch, dig a hole for a bucket under the discharge point of the siphon. Time how long the bucket takes to fill with a stopwatch. It is important that the discharge point of the siphon remains at the normal height so that the flow rate is not modified. Flow rate is equal to the volume of bucket (litres) divided by the time taken to fill (seconds).

Figure 5.3.10 Measuring head height and using theoretical flow charts to estimate siphon flow rate

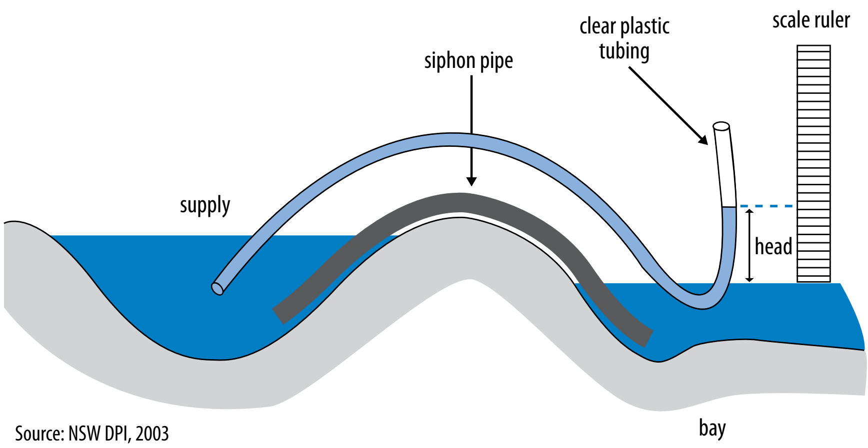
It is probably simpler to determine flow by measuring head by using a \`brickies' level (Figure 5.3.11). Start by filling the tube with water from the head ditch and then let the water siphon through the tube to remove any air bubbles. The tube is then held up so that the water level in the tube can be measured against the ruler. The measurement is taken from the middle of the discharge point of the siphon (or the water level in the furrow if the siphon is submerged) to the top of the water level in the clear plastic tubing. Then refer to the siphon flow chart in Appendix 1 to determine the flow rate for the particular siphon size and length.

For bay irrigation, flow rate for different door sizes and head heights can be obtained from Table 5.3.2.

Table 5.3.2. Door outlet flow (L/s) for a range of door sizes and head heights.

	Opening width (mm)					
Head (mm)	300	450	525	600	750	900
100	18	26	31	35	44	52
150	32	48	56	64	80	96
200	49	74	86	99	123	148
250	69	104	121	138	173	207
300	91	136	159	181	227	272

Figure 5.3.11 – A 'brickies' level



Source: NSW DPI, 2003

It is important when taking these measurements to understand that head height may vary during an irrigation event. This means that if a single measurement is taken at a time when the head is at its lowest and extrapolated over the entire event, the volume applied will be underestimated and vice-versa when the head is high. Furthermore, flow from different siphons can vary substantially due to differences in head, siphon placement, siphon diameter or siphon length. It is therefore important to measure the flow rate for a number of siphons and use an average value when extrapolating data across an entire field.

This process will often highlight the magnitude of these flow variations across a field which can be a useful insight for irrigation management. To minimise variations due to siphon placement, it is important to ensure the position of all siphons is as similar as possible to ensure uniform flow rates from each. In particular, ensure that the outlet height of all siphons is similar.

Surface irrigation evaluation services such as Irrimate (see below) include inflow monitoring as part of the evaluation procedure. This not only saves time compared to manual measurements, but the data is typically logged over the entire irrigation event so that any variation can be readily identified.

Once you have measured applied water, you will be able to calculate some basic water use indices (see WATERpak Chapter 1.2 for definitions and further information). The total water applied per hectare can be calculated by either:

1. dividing the bulk inflow by the number of hectares watered, or
2. taking the average individual furrow flow and dividing by the area watered by this furrow

As every irrigation throughout the season will be different, the total water should be calculated for each event separately and summed for the seasonal total.

For example

Total Inflow = 120 ML

Area Irrigated = 100 ha

Total Water Applied = 120 ÷ 100 = 1.2 ML/ha

Average furrow flow rate = 4.0 L/s

Irrigation Duration = 9 hours

Total Inflow

= 4.0 x 9 x 60 x 60 (convert hours to seconds)

= 129600 L = 0.1296 ML

Furrow Length = 600 m

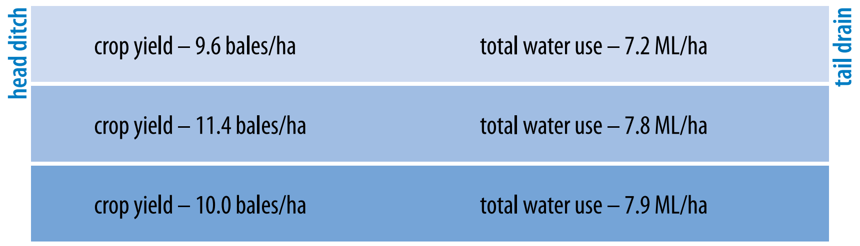
Furrows irrigated every 2 metres

Area irrigated by 1 furrow = 600 x 2 = 1200 m^2
= 0.12 ha

Total Water Applied = 0.1296 ÷ 0.12
= 1.08 ML/ha

Irrigation water use index (IWUI) can be calculated by dividing the total production from a field by the total seasonal water use. For very large fields, or where variations in yield are observed between different parts of a field, it may be more useful to calculate individual IWUI for sections of a field as illustrated in the example below.

Example



In top section

Yield = 9.6 bales/ha Water use = 7.2 ML/ha

Irrigation water use index = 9.6 ÷ 7.2 = **1.33 bales/ML**

In middle section

Yield = 11.4 bales/ha Water use = 7.8 ML/ha

Irrigation water use index = 11.4 ÷ 7.8 = **1.46 bales/ML**

In bottom section

Yield = 10.0 bales/ha Water use = 7.9 ML/ha

Irrigation water use index = 10 ÷ 7.9 = **1.27 bales/ML**

Calculating Gross Production Water Use Index (GPWUI) follows this exact same procedure except that the total water use includes effective or total rainfall. Note that rainfall can vary substantially even across a farm, so it is useful to place a rain gauge at the field to measure rainfall more accurately.

What is happening under the soil surface?

Whilst basic measurements and calculations can help you to make tactical irrigation decisions, strategic decision making about surface irrigation systems requires more detailed information about irrigation performance, uniformity and efficiency. However as previously mentioned, it is particularly difficult to measure what is happening in every part of a field directly. Surface irrigation performance evaluation techniques, such as the commercially available Irrimate service, allows irrigation performance to be evaluated by making a series of practical measurements.

Performing a surface irrigation performance evaluation requires measurement of a number of inputs.

- Inflow rate (flow meters are used to collect siphon or bay flow for the duration of the irrigation event)
- A number of advance points (the time it takes water to reach a certain distance down the field, collected by automated advance sensors)
- The dimensions of the furrow
- The depth of flow in the furrow
- Field length and slope

Advanced simulation techniques can also utilise outflow data (collected with automated flumes) and variable inflow data to improve the ability to model some irrigation events.

The rate at which the water moves down the field (advance) is influenced by the infiltration characteristic of the soil. Hence if you are able to measure the advance curve, you can determine the infiltration characteristic. After this is achieved, you can then use this infiltration characteristic to determine what might happen if you change various irrigation management parameters, such as the inflow rate or the time to cutoff.

Following data collection, the simulation model is calibrated against the measured advance data to ensure accuracy. The modelling technique has been used successfully for more than ten years across hundreds of irrigation events in the Australian cotton, grains, sugar and pasture industries.

Further information and examples of surface irrigation performance evaluation can be found in the following case studies:

Economic benefits of performance evaluation

Want a bigger farm? Buy it with furrow optimisation

Improving performance of bay irrigation through higher flow rates

Improving Surface Irrigation Performance

The performance of a surface irrigation event is influenced by a number of design and management factors. Each of these factors has a different amount of influence over the performance of an irrigation event, as illustrated in Table 5.3.3.

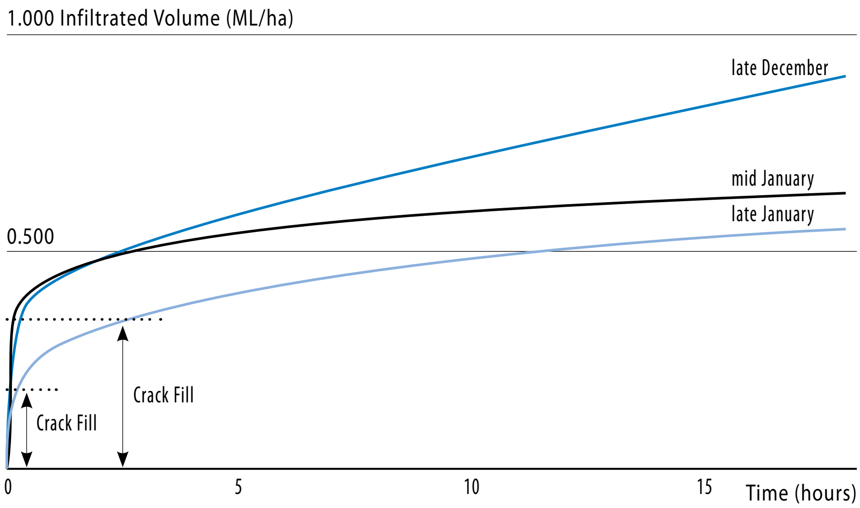
Table 5.3.3 – Effect of surface irrigation variables on irrigation performance

Variable	Influenced by	Impact on Performance	Comments
Soil infiltration characteristic	Usually cannot be influenced	***	High infiltration soil – slow advance & rapid recession
Inflow rate	Management & design	***	High flow rate – fast advance rate, potential for increased tailwater runoff
Time to cut-off	Management	***	Determines total opportunity time, deep percolation loss and tailwater volume
Length of field	Design	**	High efficiency & uniformity can be difficult on long fields
Application Depth (deficit)	Management	**	Irrigating to a deficit which is very small or very large may reduce performance.
Field Slope	Design	*	Steep slope – increases rate of advance & recession
Surface Roughness	Usually cannot be influenced	*	Rough surface – slower advance
Furrow Dimensions and Shape	Design & management	*	Furrow shape has little impact, although changes in infiltration characteristic (e.g. through compaction) may do.

*** – more impact, * – less impact

Source – Raine and Smith, 2004

Figure 5.3.12 – Cumulative Irrigation Curves demonstrating a change in infiltration characteristic over the course of a season. (Source – D. Richards, CSIRO)



Infiltration Characteristic

The soil infiltration characteristic is essentially a variable which is generally out of the control of the irrigator. In some circumstances the infiltration characteristic may vary, for example in some sealing soils the infiltration characteristic may vary during the season as the soil structure changes. Similarly the infiltration characteristic may be varied through tillage practices or when large deficits produce significant cracking.

If the infiltration characteristic does change throughout the season (Figure 5.3.12), then you should have an estimate of how these infiltration characteristics change and what management strategies should be applied, as management may need to vary.

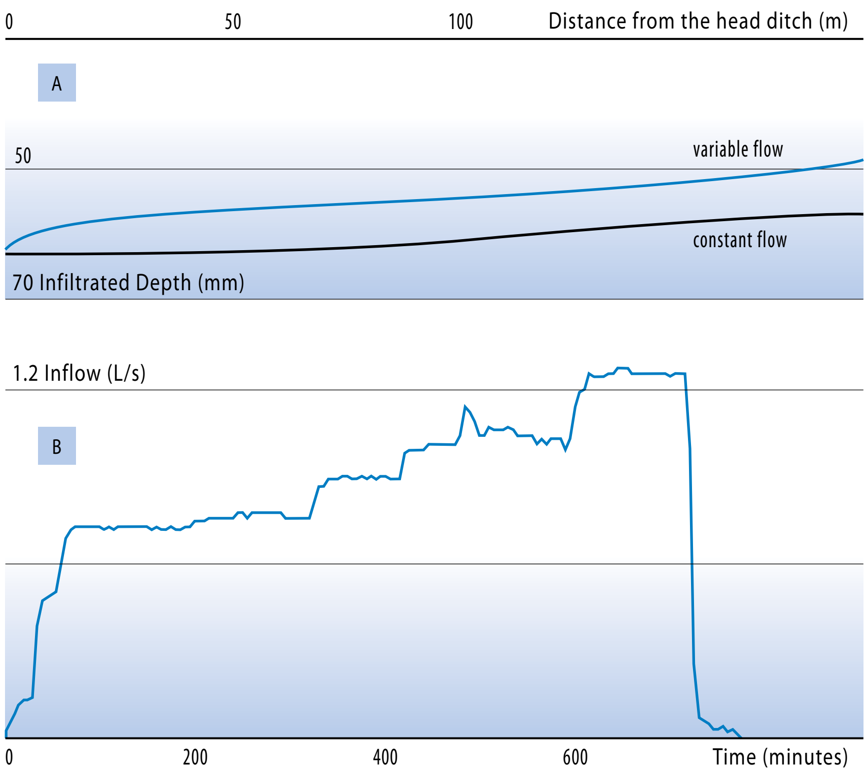
The use of Polyacrylamide (PAM) (see WATERpak Chapter 1.9) also affects the infiltration characteristic. PAM maintains an open soil structure, usually resulting in increased infiltration. For any soils where deep drainage already occurs, this will lead to increased deep drainage. It is important when using PAM to understand that this product will change the infiltration characteristic, and thus affect performance. If you have already evaluated performance without PAM, then you will need to re-evaluate the performance with PAM. The effect of PAM is typically reduced or removed following cultivation.

Inflow rate

Inflow rate has a major impact on performance due to the effect on the speed of water advance down the field. A faster advance is typically more desirable on high infiltration soils as the advance curve becomes more closely aligned to the recession curve, improving uniformity. However, as inflow rate increases, the volume of water lost as tailwater increases significantly if the cutoff time is not accurately matched. Inflow rate typically has the largest influence of any variable that can be managed by the irrigator.

Irrigation performance can be affected through both a gross change to the inflow rate as well as variations to the inflow rate during the irrigation event. Often a variable inflow rate occurs when the water level in a head ditch is not kept constant. Variable inflow may have a range of effects on different performance measures. As an example, Figure 5.3.13 shows a reduction in distribution uniformity due to an unintentional variation in inflow rate.

Figure 5.3.13. (A) Infiltrated depth profile for variable and constant (0.825 L/s) inflow (B) variable inflow hydrograph for this example (Source – M. Gillies, NCEA)



Time to Cutoff

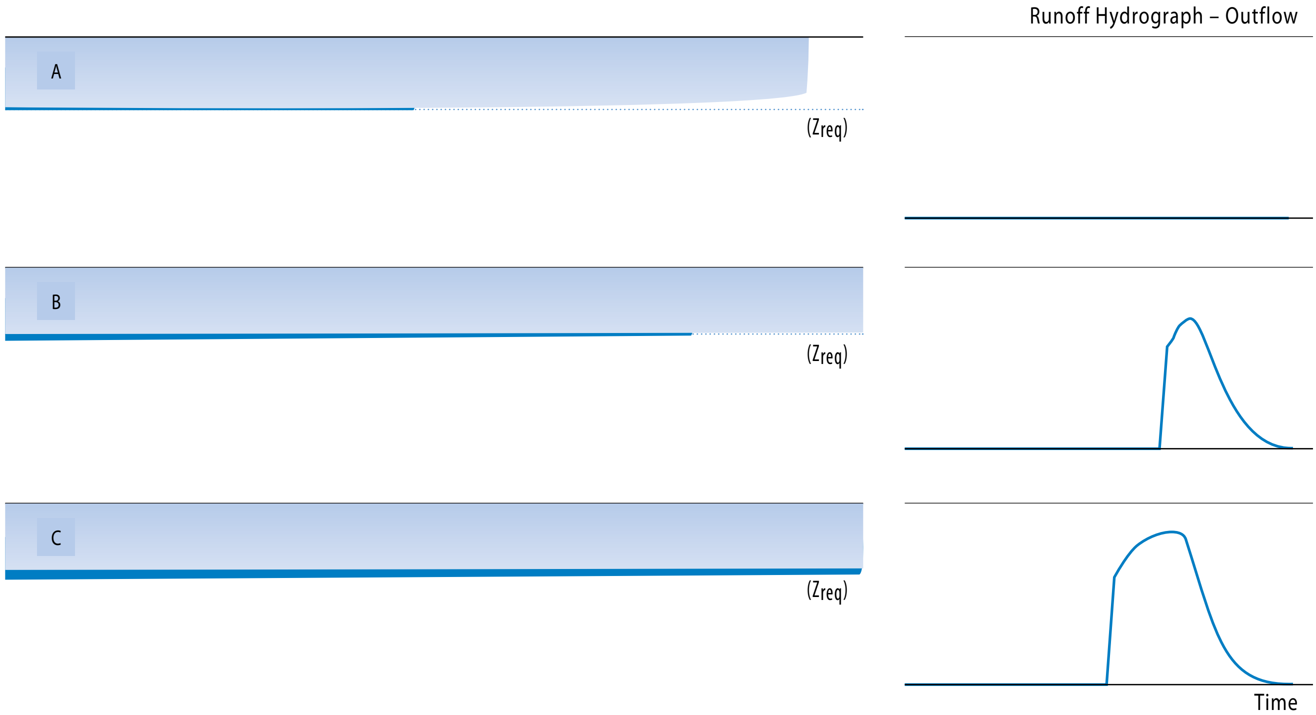
Along with Inflow rate, time to cutoff is a key variable which can be easily managed by the irrigator. In fact, it is typical for these two variables to be managed together.

Depending on soil infiltration characteristic, cutting off the irrigation too soon may result in insufficient depth of water application, poor requirement efficiency and poor uniformity. Cutting off the irrigation too late could easily result in excessive tailwater and deep drainage, decreased application efficiency and a high risk of yield loss due to waterlogging. As mentioned previously, increased inflow rate is likely to result in excessive tailwater unless time to cutoff is managed accordingly.

Figure 5.3.14 demonstrates the effect on a number of parameters of changing only time to cutoff for an irrigation event. In this case the optimum strategy is to cutoff at 320 minutes (5 hours and 20 minutes). Cutting off at 240 minutes (4 hours) meant that the water did not reach all the way to the end of the field. Cutting off at 400 minutes (6 hours and 40 minutes) resulted in more than twice the amount of tailwater and additional deep drainage. The application efficiency calculations assume an 85% efficiency in tailwater recycling.

Figure 5.3.14. The effect of cutoff time for an event where inflow = 6 L/s and field length = 520m. Optimum cutoff time is 320 minutes.

Scenario	A	B	C
Time to Cutoff (mins)	240	320	400
Inflow (ML/ha)	0.83	1.11	1.38
Outflow (ML/ha)	0.00	0.17	0.41
Infiltration (ML/ha)	0.83	0.94	0.98
Deep Drainage (ML/ha)	0.01	0.07	0.11
Application Efficiency (%)	> 95	87	84
Requirement Efficiency (%)	90	100	100



Field Length

Field length can influence distribution uniformity because the advance rate becomes slower as the irrigation water has to travel further down the furrow. This makes it more difficult to obtain advance and recession rates which provide for a similar opportunity time along the length of the furrow.

Such non-uniformity can impact upon efficiency by increasing deep drainage at the top end of the field. Field length cannot be managed between irrigation events. However modifying existing furrow lengths may be an appropriate strategy for some situations in the design phase (Table 5.3.4).

Table 5.3.4. Improved performance due to a change in field length and management

	Original Field Performance	Performance following change in field length
Field Length (m)	885	408
Flow Rate (L/s)	2.70	3.8
Time – Water Applied (hr)	20	6
Deficit (mm)	60	60
Inflow (mm)	110	83
Tailwater (mm)	27	21
Water Infiltrated (mm)	83	62
Application Efficiency (85% of tailwater recycled)	69	92
Distribution Uniformity – DU (%)	92	92
Potential Water Saving (ML/ha)		0.22

(source – R. Jackson, NSW DPI).

Application Depth (Deficit)

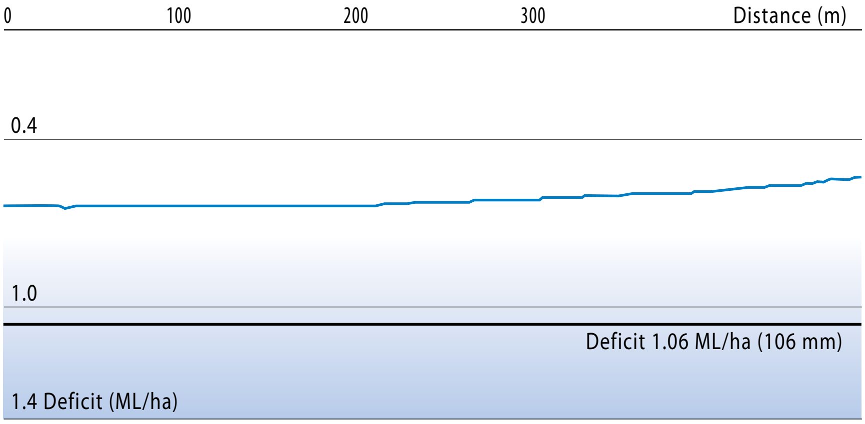
The application depth for a surface irrigation event is typically viewed as being fixed, as determined by the amount of crop extraction since the last full irrigation. Whilst this is often the case, there are two circumstances in which deficit may become a management variable:

1. In some soils, it may be possible to apply less than the total deficit. This may allow for increased application efficiency, although irrigation frequency will need to be increased. However, in some soils, particularly highly cracking clay soils, it may be difficult or impossible to apply less than the total deficit due to the presence of cracks.

   Conversely some soils have poor infiltration where deficit irrigation is likely to occur as a matter of course. In these situations performance may well be high, although there is insufficient water infiltrating the soil and being made available for the crop.

Be careful – deficit irrigation may allow for improved performance and ability to capture rainfall, but there is less moisture buffering in the soil and a greater number of smaller irrigations will be required.

Figure 5.3.15. Example of a deficit irrigation event where the amount of water applied is less than the deficit at the time of irrigation



(Source – R. Jackson, NSWDPI).

2. It may also be possible to apply irrigation events earlier or later in order to influence the total deficit at the time the irrigation takes place. Often irrigating to a smaller deficit will allow for a faster advance rate. This may be useful in soils where it is difficult to obtain a fast advance rate when the deficit is large due to the presence of large cracks. Modifying irrigation frequency may also have agronomic impacts.

   Sometimes irrigation intervals are stretched so that less irrigations are required during the season. However, stretching irrigation events may have a negative impact on the performance of surface irrigation systems because the larger soil moisture deficit will decrease the rate at which irrigation water will advance down the furrows, subsequently affecting opportunity time and distribution uniformity. It may be possible to increase the inflow rate to help to offset these effects.

Table 5.3.5. Example of water applied to different irrigation strategies on the Darling Downs

	Early Strategy	Normal Strategy
Deficit at Irrigation (mm)	80	100
Number of Irrigations	5	4
Water Applied each Irrigation (ML/ha)	1.4	1.65
Total Water Applied (ML/ha)	7.0	6.6
GPWUI (B/ML)	1.66	1.63

(Source J. Hare, QDPI&F)

Determination of application efficiency and requirement efficiency rely on the accuracy of the deficit before irrigation. Errors in the deficit value may influence these parameters by inaccurately determining the proportion of water applied to the root zone.

Field Slope

The field slope has very little influence on the rates of advance and recession, and virtually no impact on performance. Hence modifying slope without first determining the effect on performance may have very little benefit, particularly for the potentially high cost of earthworks involved.

For the irrigation event in Figure 5.3.15, there was absolutely no difference in performance between a slope of 1 in 10000 (0.01%) and a slope of 1 in 1000 (0.1%). The water arrived 28 minutes sooner on the steeper slope (309 mins vs 347 mins), but this did not impact on performance.

A field with variable slope may have a greater impact, particularly where melon holes or similar depressions actually create a minor uphill slope that allows water to pool temporarily. However, some variation in slope may actually 'even out' poor performance cause by other factors such as changes in soil type (infiltration characteristic).

It is **vital** to investigate current performance before spending large amounts of money on modifying slope if the aim of the earthworks is to improve irrigation performance.

Surface Roughness

The roughness of the soil surface provides a resistance to the flow. Typically the surface roughness is not something that can be readily controlled, although it may be modified somewhat due to cultivation practices, stubble retention, etc.

An increase in surface roughness leads to a reduction in the speed of advance across the field and usually only slightly influences performance.

Evaluation Results

When you have a surface irrigation performance evaluation performed, it is typical to receive a report that demonstrates the measured performance, as well as one or more alternative management strategies that could be implemented, and the likely performance of these strategies.

Interpreting these results is usually a matter of comparing the various performance measures (as discussed earlier) for the different optimised scenarios and determining which of the options can be practically and economically applied.

Usually, evaluations have been undertaken for a few different events during the season, so it is important to remember that the optimum practice for an early season irrigation may not be the same for an irrigation event later in the season.

Case study

Data from fields in two different cotton-growing regions was collected and analysed to determine the application efficiency and distribution uniformity as well as the maximum inundation time (Table 5.3.6). Maximum inundation time (the largest infiltration opportunity time) is important to many growers, as longer periods of inundation are likely to be detrimental to crop productivity (and indicate potential waterlogging). The strategies investigated for improved performance included (where appropriate):

- cut-off when water reached the end of the field
- cut-off one hour before water reached the end of the field
- increased application rate (inflow)
- increased application rate, and cut-off when water reached the end of the field

It should be noted that these strategies were selected as representative of the types of changes possible and whilst leading to increased performance in these situations may not be the choices that lead to optimum performance. Optimum performance needs to be assessed on an individual basis. Field 1 data is sourced from Raine and Walker (1998).

Table 5.3.6 - Case Study: Irrigation performance for a selection of different management strategies on two fields.

	Typical management	Cut-off when reached end	Cut-off one hour before end	Increased application rate	Increased application rate and cut-off when reached end
Field 1					
Application rate (L/s/furrow)	2	2	2	4	4
Cut-off time (min)	918	745	685	552	377
Inundation time (min)	990	810	732	600	396
Application efficiency (%)	70	86	93	58	84
Requirement efficiency (%)	100	99	99	100	99
Distribution uniformity (%)	93	92	90	97	95
Field 2					
Application rate (L/s/furrow)	3	3	3	4	4
Cut-off time (min)	680	380	320	300	232
Inundation time (min)	692	392	335	315	245
Application efficiency (%)	46	82	89	68	87
Requirement efficiency (%)	100	99	91	100	98
Distribution uniformity (%)	94	86	63	92	88

For both fields, the data indicates the variations in application efficiency and distribution uniformity. It should be noted that some strategies may have improved either efficiency or uniformity but not all strategies improved both. For both of these fields, the best strategy of those tested in terms of application efficiency, distribution uniformity, requirement efficiency and inundation time was an increased application rate and decreased cut-off time. In both cases the period of inundation was reduced by over half and the application efficiencies were increased substantially with little effect on the already high requirement efficiency and distribution uniformity.

The strategy of having a cut-off time one hour before the water reached the end of the field was unsuccessful for Field 2 because insufficient water was applied to the bottom of the field: hence the values for distribution uniformity and requirement efficiency are reduced.

Implications of Management Changes

Precision – Stick to the Prescription

Often (although importantly, not always), improved performance is obtained from a combination of increased inflow rate and decreased time to cutoff. When inflow rate is increased, more precise control is typically required as it becomes easier to adversely affect performance when the inflow rate is high.

For this reason, it is important to objectively evaluate your system performance, rather than simply increase the inflow rate using some kind of *Rule of Thumb*.

One of the major secondary effects that occurs when increasing inflow rate is that the opportunity for larger volumes of tailwater is increased. This is illustrated in Table 5.3.7, where a measured irrigation event had an inflow rate of 2.63 L/s for a duration of 860 minutes. In optimising this irrigation event, the recommended change was for an inflow rate of 6 L/s for a duration of 320 minutes. Management for this scenario must be more precise to capitalise on the benefits of the recommendation.

The table demonstrates the volume of water applied and runoff if the siphons are left for periods of time in excess of the recommendation. For example, if the optimised event is left to run for an hour longer than the recommendation (a total of 380 minutes), not only has there been more runoff than for the measured event, but also more than if the measured event had run for an extra hour (a total of 920 minutes).

The infiltrated amount and potential for deep drainage may also be adversely affected.

Table 5.3.7. Control of cutoff time becomes more important as flow rate increases

	Measured Event	Optimised Event
Field Length (m)	520	520
Flow Rate (L/s)	2.63	6
Time – Water Applied (min)	860 14 hrs 20 mins	320 5 hrs 20 mins
Time – Advance to end of field (min)	710 11 hrs 50 mins	310 5 hrs 10 mins

Additional Time to Cutoff (hr)	Measured Event (ML/ha)		Optimised Event (ML/ha)	
	Inflow	Outflow	Inflow	Outflow
0	1.31	0.25	1.11	0.17
0.5	1.35	0.29	1.21	0.26
1	1.39	0.33	1.32	0.35
1.5	1.44	0.37	1.42	0.44
2	1.49	0.40	1.52	0.54
2.5	1.53	0.44	1.63	0.63
3	1.58	0.48	1.73	0.72

Often the volume of tailwater is dismissed as being only a minor cost; however it is important to understand that there are a number of reasons to manage tailwater volumes. It is not uncommon for the cost of pumping tailwater to be in the order of $20 per ha.

In the example above, the measured event had tailwater of 0.25ML/ha per irrigation. For 7 irrigations with a pumping cost in the order of $10/ML, this is a total of $17.50 per ha.

In addition, research has shown that it is possible to lose 15% of tailwater as it is recirculated around the farm. Therefore as the volume of tailwater increases, so do the potential losses. Finally, there is often little thought given to the secondary effects of tailwater such as sediment and nutrient losses. Recent research has indicated that the quantities of sediment and nutrients being lost in tailwater can be significant, and that the concentration of these generally increases with the flow rate.

Nutrient and Sediment Losses

It is not uncommon for 1 t/ha of sediment per season to be lost from surface irrigated fields in irrigation tailwater only, in addition to losses from rainfall runoff. As the flow rate increases, the concentration of sediment and some nutrients increases.

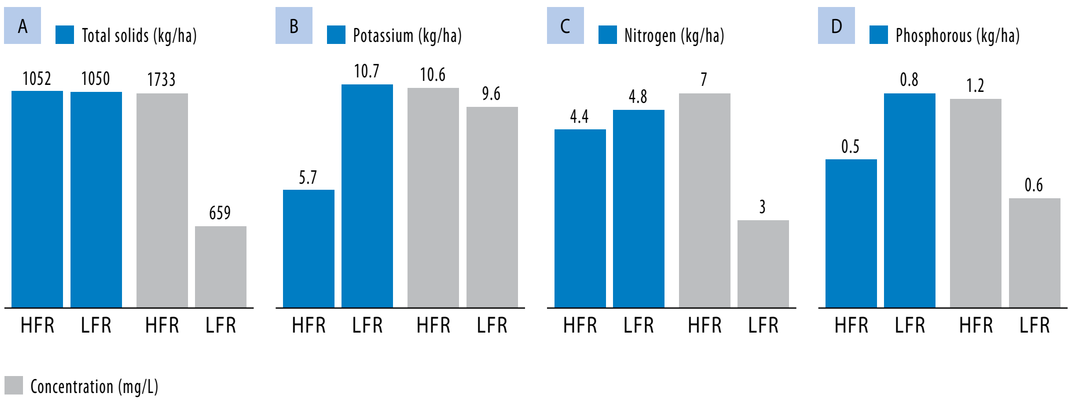
Therefore the total volume of tailwater must be reduced accordingly to prevent an increase in these sediment and nutrient losses.

Figure 5.3.16 shows the results of the analysis of irrigation tailwater for every event of a single field in the Dawson Valley for the 2005-06 season. The concentration of various contaminants was measured over the duration of the runoff event and was scaled up by the volume of tailwater measured to give the total amounts indicated below.

For all of the contaminants, the concentration was greater when the flow rate into the furrow was higher. However, the total amount of contaminant was lower because the volume of tailwater was reduced accordingly. If the cutoff time under the high flow rate scenario was not correctly selected and the volume of tailwater was too high these figures would change dramatically.

The low flow rate was the grower standard practice at 1.5 L/s and the high flow rate was the improved practice at 4 L/s. The field was approximately 700 metres long.

Figure 5.3.16. The total amount and concentration of (A) Total Solids (B) Potassium (C) Nitrogen and (D) Phosphorus removed from a field trial site in a single season (Source – A. McHugh, NCEA).



HFR – high flow rate, LFR – low flow rate,

The volume of tailwater is also a significant consideration when water running urea, as much of the Urea being applied may leave the field in the tailwater.

Agronomic Management

As we have seen, the performance of surface irrigation events can be influenced by the infiltration characteristic of the soil, which in turn can be influenced by the deficit at which an irrigation takes place. For this reason, irrigation scheduling can influence the performance of a surface irrigation event. There are subsequently many related agronomic impacts associated with irrigation scheduling.

- A smaller irrigation deficit will influence performance by typically increasing the rate of advance. This may lead to a greater number of smaller applications. Agronomically, smaller deficits **may** promote rank growth in indeterminate crops, such as cotton, due to the balance between vegetative and reproductive growth.
- A large irrigation deficit will influence performance by typically decreasing the rate of advance. This may lead to fewer large irrigations. If the deficit is too large the plant may stress too much before the irrigation takes place.

Regardless of the scheduling chosen, if the irrigation event is not managed accordingly, performance may be adversely affected.

Many other practices can also influence, surface irrigation performance, such as:

- Stubble retention in furrows
- Use of Polyacrylamide (PAM)
- Soil treatments and surface cracking
- Mulch cover
- Row configuration

It is suggested that appropriate monitoring of plant stress or soil moisture, along with evaluation of irrigation performance, will provide the information necessary to maximise both plant productivity and water use efficiency.

Future developments in surface irrigation performance

The past decade has seen a dramatic increase in the performance of surface irrigation within the industry, largely because of improved measurement techniques as well as a better understanding of the implications of irrigation management decisions such as waterlogging and deep drainage.

Whilst the improvements in surface irrigation management and measurement have been significant, ongoing research has identified a number of further improvements that have the potential to offer a 'second wave' of improved surface irrigation management.

Measurement and simulation

The techniques used to evaluate surface irrigation performance have continually evolved since their introduction to the industry in the late 1990's. Hardware has been continually upgraded to be more robust and user friendly. Similarly, the techniques used to determine soil infiltration characteristics and to simulate irrigation events have been improved to broaden their application and ensure the highest degree of accuracy.

For example, the current generation of simulation modelling, SISCO, provides enhanced functionality and the ability to automatically optimise irrigation management for a given set of management constraints.

Performance measurement techniques have typically involved sampling a small number of furrows (typically four to eight). To ensure that the results from this approach can be applied across an entire field, measurements are usually taken in a section of field that is believed to be representative. Whilst this approach has undoubtedly been successful, the ability to investigate variability across entire fields is likely to lead to even greater improvements in the future.

Recent research by the National Centre for Engineering in Agriculture (NCEA) has led to the development of techniques that build on existing data to reduce the amount of information required from individual furrows. For example it is now possible to predict soil infiltration characteristics using only a single advance point instead of four or more as is the typical current practice.

In addition, NCEA researchers have developed a whole field simulation model called IrriProb, which expands existing techniques to measure performance across the entire field and to optimise irrigation management so that whole field performance can be maximised.

Automation

Automation is the application of technology to undertake actions that would normally be performed by a human. Conceptually, automation is not new, although it has not historically been applied to surface irrigation systems within Australia in a substantial way. However automation systems are becoming more widespread in bay irrigation systems in Southern Australia, where it is possible to quite simply provide automatic control of irrigation inlets. A range of systems are now available which will allow irrigation events to be operated according to a set program or via a transmitter from the farm office or, potentially, mobile phone. Such systems are seen as attractive as a labour saving device.

Automation is somewhat more difficult to establish in furrow irrigation systems due to the fact that these systems are generally supplied by siphons. However a recent trial in the Gwydir valley applied automation to a pipe through the bank system. Combined with some of the lessons learned in PTB management from the case study referenced earlier in this chapter, automation of furrow irrigation systems seems achievable.

In addition to in-field labour savings, automation also has the advantage of potentially being able to streamline irrigation management of the whole farm. For example, it is possible to apply automated components to storages and channels, as well as fields, so that water can be managed around the whole farm. Combined with accurate water metering, such a system could ensure that releases from storages are accurately matched to in-field requirements, minimising fluctuating water levels in channels and preventing excessive losses through channel overflow structures.

Precision irrigation and adaptive control

Perhaps the most exciting future opportunity for surface irrigation is the combination of advances in these categories. Adaptive control systems allow individual irrigation events to be automatically and continuously re-adjusted so that irrigation performance can be optimised and variability can be accounted for.

Just like other precision agriculture systems, precision irrigation involves a system that can adapt to the field conditions and can be managed to achieve the desired level of performance. It is possible for any type of irrigation system to operate as a precision system and recent research at the NCEA has demonstrated this concept on both CPLM and surface irrigation systems (also see page 41 of the Australian Cotton Water Story).

For surface irrigation systems, adaptive control requires:

- the ability to automatically control the irrigation (e.g. through automation);
- the ability to measure the progress of the irrigation;
- the ability to simulate and optimise the irrigation event as it occurs; and
- the ability to modify the control of the irrigation event to match the optimised conditions.

Full precision is realised by monitoring and modelling crop growth and response to irrigation throughout the season and using this information to determine the amount and timing of irrigation that gives the desired results.

Practically, this means that the irrigation system of the future will be able to predict when irrigation is needed, and then optimise the performance of the irrigation event whilst it is underway. This approach provides the potential for significant performance advantages. For example a trial in 2011-12 showed yield improvements of 10 per cent and water savings of 12 per cent when compared with the grower treatment.

Further Information

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5.4 Bankless channel irrigation systems

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Key points

- Bankless channel irrigation systems are an alternative method of surface irrigation
- Bankless channel is appealing as it offers labour savings and machine operation efficiencies over traditional siphon irrigation
- Irrigation performance of bankless channel irrigation is difficult to measure and hence aggregated performance benchmarks have not been produced
- A simulation model is being developed to aid design and management of the system.

Introduction

Bankless Channel Irrigation Systems (BCIS) were developed in the 1990s in southern New South Wales with more recent modifications made to suit row-cropping enterprises in southern Queensland. While there are variations in the slopes and configuration of the systems, all of these systems operate by spilling water from a below-surface-level channel into an adjoining bay.

This section provides an overview of BCIS, the advantages and disadvantages of these systems and a guide to evaluating irrigation performance.

Why Bankless?

Irrigators who pioneered BCIS were seeking to reduce the labour cost associated with siphon systems without the additional energy costs associated with pressurised alternatives. In addition to the labour savings and a low energy requirement, BCIS also offered increased in-field machine efficiencies as the ability to drive through the bankless channel and turn on an adjoining roadway allowed for rapid re-entry to the field without the encumbrance of rotobucks.

The system also allows irrigation of a wide variety of crops including, for southern irrigators, the ability to include rice into a row-cropping rotation. Advantages and disadvantages of the system are highlighted in Figure 5.4.1.

System description

Two main design approaches are currently being used for BCIS. The conventional form of BCIS consists of a series of terraced bays with a vertical separation of between 0.1to 0.2 m. Bays typically have either a zero or very shallow positive (uphill) field slope of around +0.01% (1:10000).

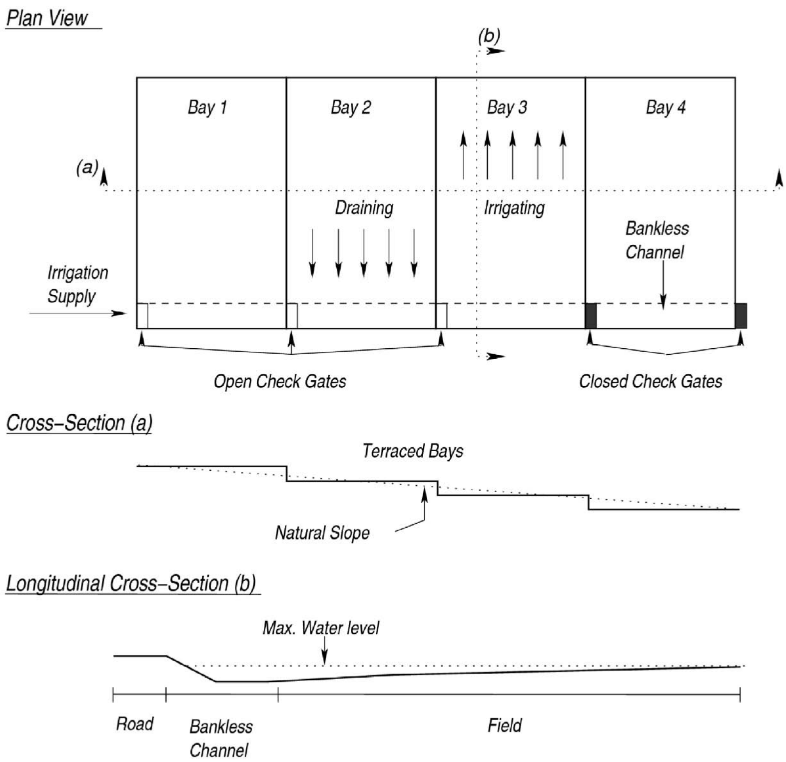
Bays must have no cross-slope and can be configured with beds or flat-planted. All bays are connected by a bankless channel (Figure 5.4.1). However, each bay is irrigated individually by backing-up water behind a closed structure in the channel, causing water to rise and spill into the adjacent bay. Once irrigation is complete for that bay, water is released through the structure, allowing both supply water from the channel and drainage water from the bay to flow into the next bay in the series. This process is repeated until all bays are irrigated.

The flow into each bay is augmented by the runoff from the accumulated surface storage volume in each preceding bay. This creates a higher discharge rate, which means fast advance rates can be achieved.

Table 5.4.1. Advantages and disadvantages over Siphon Irrigation

Advantages	Disadvantages
Labour savings	Larger footprint for a given area due to check banks and bankless channel
Machine efficiencies	Not suited to steeper slopes
Cropping options	Laser grading must be precise
No tailwater during irrigation	Development costs
Silt is minimised	Challenging to evaluate
Faster stormwater clearance	Management for uniformity can be challenging
Able to pond water for rice production	
Can achieve 4-6 hr changes	

Figure 5.4.1. Plan and cross section views of a BCIS showing flows during irrigation of the third bay in a series of four bays. Cross-section (a) shows the terraced bays with regards to the natural slope, while cross-section (b) shows a longitudinal section of the bay.



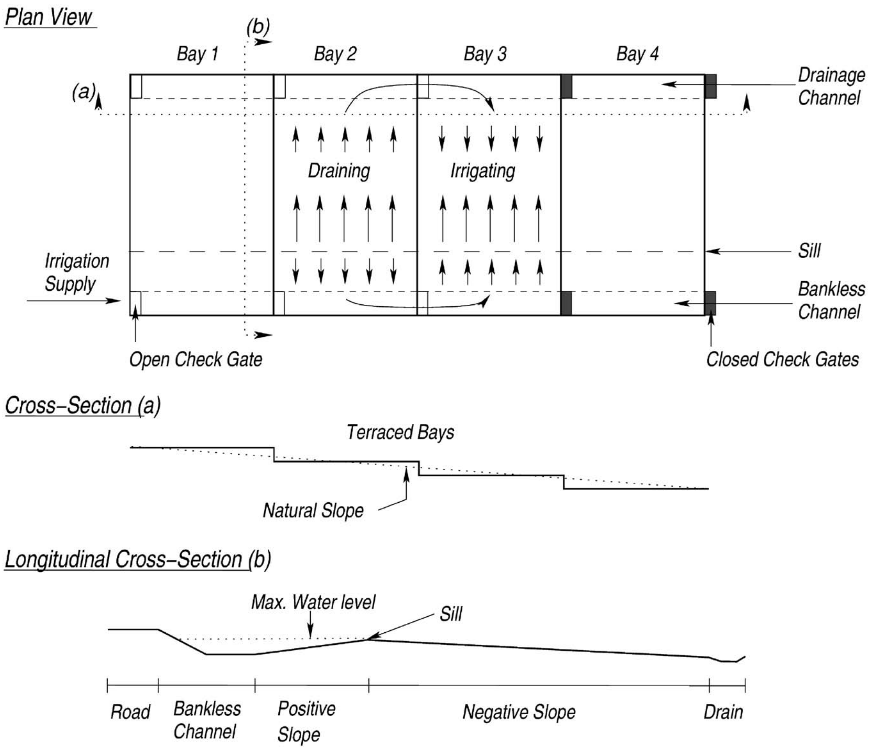
The second design approach of BCIS uses the same approach as the conventional form to deliver water to a bay in that water spills from the bankless channel into the adjacent bay. However, in contrast to the conventional form, approximately 20 metres from the bankless channel, the bay slope changes from a positive field slope to a conventional negative field slope, as show by the 'sill' in Figure 5.4.2.

The advantages of this design over the conventional design are shown in Table 5.4.2. A case study of this design approach is available online.

Table 5.4.2. Advantages and disadvantages of a silled system over conventional BCIS

Advantages	Disadvantages
Development costs less than rooftop Bay inflow/outflow	Unable to pond water such as for rice
Less field earthworks	Largely untested performance
Inundation time more consistent down the furrow	Not suited to hard-setting soils
Evaluation is easier	

Figure 5.4.2. Plan and cross section views of an alternative BCIS.



Performance Evaluation of BCIS

The purpose of evaluation is to understand the relative irrigation performance of a system and identify areas in which performance may be improved. Considerable discussion on irrigation evaluation and water efficiency is provided in WATERpak Chapter 1.2.

Unfortunately, some aspects of conventional surface irrigation evaluation methods cannot be applied to BCIS due to the positive field slope and the interconnected nature of bays within these systems. Consequently, few evaluations examining the irrigation performance of entire systems have been conducted.

However, recent evaluation methods suited to conventional BCIS have been developed following experimentation in the Murrumbidgee Irrigation Area on two field sites. Suggested field measurements, the information they provide and a collection method are described in Table 5.4.3.

Table 5.4.3. BCIS evaluation measurements and the information they provide.

Measurement point	Information provided	Collection Method
Bay inflow/outflow	Bay scale application depths and inlet hydrographs for simulation of irrigation within furrows.	Flow meters installed at bay inlets/ outlets
Furrow discharge	Infiltration parameters	Detailed measurement of furrow cross-sections, flow velocity and depth. Note: considerable care must be taken not to restrict discharge.
Furrow advance	Infiltration parameters	In-furrow advance meters
Furrow entrance elevation survey	Within-bay uniformity	Standard survey methods
Soil moisture	Change in soil moisture	Volumetric or calibrated capacitance measurement devices

The collection of these parameters provides sufficient information for estimates of irrigation performance to be determined with values for DU, Potential Application Efficiency and the Average Infiltrated Depth calculated.

The evaluation results indicated that variability in applied depths between the bays of BCISs may be greater than with-in bay variability. This suggests that careful management of irrigation timing and flow rates may allow the performance of a system to be improved.

Simulation of a field may be used to identify specific timing and flow rates which best suit a particular field. Simulation models enable parameters to be adjusted to reflect field conditions and may assist in identifying superior designs. A simulation model is under development which is capable of accommodating the design aspects of these systems. The model is being developed to simulate irrigation across an entire field. This means that the hydraulic interactions that occur between bays can be better managed to improve the performance of BCISs.

Until such models are developed, identification of suitable times and flow rates which improve irrigation performance will remain a challenge for irrigators. However, better understanding of evaluation methods suited to this system will enable further case studies to be conducted, providing a useful insight into the performance of these systems.

5.5 Centre pivot and lateral move systems

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Key points

- Ensure the system capacity of centre pivots and lateral moves (CPLMs) is large enough, when managed correctly, to keep up with peak crop water requirements.
- Using larger diameter pipe spans costs more, but lifetime running costs are dramatically reduced.
- Sprinkler packages represent less than 7 % of the capital investment but are responsible for 70% of the irrigation performance
- Modern low pressure sprinklers have application efficiencies up to 95% and LEPA systems have application efficiencies up to 98%."
- Wheel ruts and bogging will reduce as tracks compact and can be overcome by modifying flowrate, sprinkler type and emitter location around towers to avoid placing water in wheel tracks.
- Ensure that all water drains from span pipes, to avoid corrosion. Test irrigation water quality before you buy a system, to ensure compatibility of irrigation waters and pipe coatings.
- Continue irrigation long enough after fertigation has finished to ensure machine is fully flushed.

This chapter has been updated with information from the Centre Pivot and Lateral Move training course developed by the CRC for Irrigation Futures. This course contains the most up to date information on centre pivot and lateral move irrigation in Australia and is strongly recommended for those who currently manage or are interested in purchasing these systems. This training is currently provided by a number of providers including NSW DPI and Growcom.

Additional background material and insights from current CPLM users is contained in the publications CPLM machines in the Australian cotton industry (2001) and Review of CPLM systems in the QMDB (2011) which are also strongly recommended.

History of centre pivot and lateral move machines

Centre pivot and lateral move irrigation machines (CPLMs) represent the largest (in both physical size and flow rate) of the mobile machines used by growers to apply water to crops and fields. The first CPLMs were developed in the late 1940s with the patenting of a 'self-propelled sprinkling irrigation apparatus' by Frank Zybach in Nebraska. A.E. Trowbridge manufactured these early machines. Prior to this time, sprinkler irrigation was commonly performed using steel pipe and impact sprinklers, as aluminium pipe was only just becoming available. These early centre pivot machines consisted of towers that supported the pipes via suspension cable and were powered by the irrigation water pressure using hydrostatic drives at each wheel set. The right to manufacture these machines was acquired in the 1950s by Robert Daugherty who began manufacturing under the 'Valley' brand name. The first Australian innovation in this arena saw the Layne and Bowler Company of the USA introduce the Australian Raincat ideas of electric motor drives, today's standard bowstring truss suspension and track drives which were later replaced with rubber tyres. During the 1960s, machines also started to be manufactured with water piston or water spinner drives rather than oil hydraulic drives. The standard machine manufactured prior to 1970 was a high-pressure unit (~80 psi at the centre) fitted with large impact sprinklers located along the top of pipe. However, the energy crisis in the early 1970s resulted in the introduction of low-pressure static plate sprinklers located on droppers below the pipe. These modifications meant that the machines could be operated at much lower pressures (<40 psi) with lower operating costs.

By the mid-1970s, centre pivot and lateral move machines were rapidly starting to dominate the new and expanding irrigation developments in the USA and the Middle East. Of the 25.6 million hectares currently irrigated in the USA, approximately 32% (or 8.1 million hectares) is irrigated with this equipment. Centre pivots were first introduced into Australia in the 1960s, primarily in South Australia and Victoria. Centre pivot and lateral move machines currently irrigate 8% to 10% of the total irrigated area in Australia. Centre pivot irrigation of cotton has been undertaken in the USA since the late 1960s and in Australia since the early 1970s.

The last thirty years have seen the four main CPLM manufacturing companies based in Nebraska (Valley, Lindsay Zimmatic, T&L, and Reinke) dominate the world market for these machines. There are approximately 500 machines sold in Australia each year and around thirteen manufacturers or distributors. However, the majority of the machines available in Australia are manufactured in either the USA or Europe, with only a handful being manufactured by Australian companies.

In most cases, the irrigators are imported as whole machines. Most manufacturers produce lateral move machines, but USA based companies in particular are often not interested in supplying them due to the comparatively small market size and the additional level of complexity associated with controlling and guiding these machines.

CPLM Adoption Drivers

Since the late 1990's, there has been renewed interest in CPLM systems in the cotton industry, and the amount of local research over this time has also increased in response. Notably, users of CPLM systems have been interviewed in both 2001 (across the whole cotton industry) and 2011 (across the Queensland Murray-Darling Basin only), providing a range of insights into why growers are finding these systems attractive and how they are being used. The full results of these studies are strongly recommended for irrigators considering these systems.

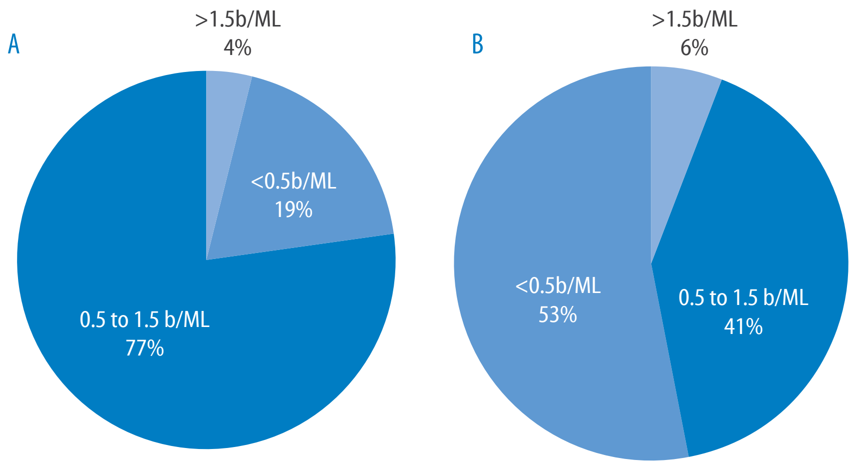
Most growers cite labour and water savings as their main motivation for installing CPLM systems (Table 5.5.1). In the 2011 study, the median labour requirements for centre pivot and lateral move systems were found to be 20% and 40% of that required for an equivalent area of furrow irrigation, respectively.

Table 5.5.1 - Comparison of issues driving adoption in 2001 and 2011

Issue	2001 Response	2011 Response
Labour Saving	85%	90%
Water Saving	93%	87%
Reduced Waterlogging	73%	60%
Improved Water Application Uniformity	65%	40%
Fertigation	46% (including chemigation)	30%
Increased Crop Yield	46%	23%
Improved Crop Quality	12%	20%
Automation	58%	20%
Chemigation	-	7%

In terms of water use, growers in the 2001 study tended to see greater improvements in Irrigation Water Use Index (IWUI, bales/ML), which may be because furrow irrigation performance across the industry has increased over the last decade with improved management practices. Still, over 40% of growers in the 2011 study believed they could achieve between 0.5 and 1.5 bales of extra production per ML of irrigation water with CPLM systems compared with furrow irrigation (Figure 5.5.1).

Figure 5.5.1 - Increase in irrigation water use index (IWUI) for cotton irrigated by CPLM compared to furrow irrigation in (a) 2001 and (b) 2011.



Other adoption drivers include the ability to irrigate a range of crops, to irrigate soil that was marginal for surface irrigation, to capture increased rainfall and to irrigate greater slopes. Individual growers have also found advantages in the ability to increase cropping intensity and to better implement minimum till practices than under furrow irrigation.

Equipment overview

Centre pivot systems are usually no longer than 500 metres, with the most common size being around 400 metres long. Lateral move machines are not commonly used overseas, and, when used in other crops, are rarely greater than 500 m long. The popularity of large machines in the cotton industry has resulted in lateral move machines of up to 1200 m in length being installed locally.

The main components of these CPLMs are the self-supporting frame spans. These structures use the water delivery pipes (located along the backbone of the span) as compression members that are held together by tie-rods acting as tension members. The pipe spans are supported at each end by a tower that incorporates gearboxes, drive wheels and either an electric or a hydraulic drive motor. Emitters (either sprinkler heads or low energy precision application fittings) are attached either directly to sockets on the main pipe or suspended closer to the crop on either rigid or flexible droppers.

Flexible mechanical and hydraulic couplings that allow the separate spans to act as individual elements connect individual spans. This ensures flexing, rotating and twisting of the joint and spans so that the machine can traverse land contours and obstacles. Machine speed governs the volume (depth) of water applied in each pass, while system alignment is maintained via micro switches, alignment levers and control equipment.

Centre pivots consist of a number of spans attached to a fixed centre tower containing a water supply point and power source around which the other spans and towers rotate (Figure 5.5.2). Lateral move machines are constructed in a manner similar to centre pivot machines except that they do not have a central rigid supply point: instead, they have the water supply point located either in the middle or at one end of the machine on a cart-tower assembly containing a mobile power plant. Lateral move machines that are supplied from open channels are provided with a large lift pump, while hose-supplied systems are fitted with an attachment point for connection to the watermain hydrant via a flexible water delivery hose.

Figure 5.5.2. Centre pivot irrigation machine showing centre tower, spans, and wheel towers

Spans and pipe sizes

Spans commonly range in length from 34.2 m (113 ft) to 62.4 m (206 ft) with variations in exact size between different manufacturers. Span lengths are commonly limited due to the weight associated with the pipe itself and the volume of water transported. Internal diameters of the span pipes range from 135 to 247.8 mm with the most common pipe sizes being 162, 197 and 213 mm. Typical pipe wall thickness is about 2.77 mm (0.11") for these systems.

Sprinkler Package

The sprinklers, nozzles and pressure regulators along the length of CPLMs are all part of the sprinkler package, and together they represent about 7% of the capital cost but are responsible for 70% of the irrigation performance. In the 1960s, CPLM irrigation systems had standard high-pressure (greater than 50 psi or 340 kPa) impact sprinklers mounted on top of the spans.

Modern low pressure sprinklers were developed to operate at less than 30 psi (200 kPa) to minimise energy requirements and have a larger and more consistent droplet size that results in very minimal evaporation. Low energy precision application (LEPA) systems were also developed to apply water directly onto the soil surface or below the crop canopy to eliminate evaporation from the plant canopy and reduce the wetted soil surface and soil surface evaporation.

Most modern emitter components (either sprinkler or LEPA attachment) are plastic with interchangeable components so that, for example, nozzle size or plate type can be easily changed. The components are often colour coded for ease of reference.

For centre pivots, as the radial distance from the centre of the pivot increases, each emitter must provide water for an increasingly larger concentric ring of field area (Table 5.5.2). This is achieved by increasing nozzle size whilst maintaining emitter spacing, maintaining nozzle size whilst decreasing emitter spacing or a combination of both.

The result is a set of sprinklers and nozzles that are precisely specified for each outlet. If the wrong emitter is put in the wrong location, the performance of the package can be completely upset. Diligence is needed here by installers and by maintenance crews to ensure the correct emitter is put in the correct location to start with, and that they are kept there whenever maintenance is done.

This is not an issue on lateral move systems where sprinkler spacing and nozzle size is generally not altered along the length of the machine when pressure regulated. However, nozzle sizes across any machine should not be changed without considering the impact on the whole system and the possible changes to pump operation that may be required.

Table 5.5.2 – The proportion of total water applied from successive centre pivot spans (G Harris, DAFF Queensland)

Number of Spans								
Span	**5 Span**	**6 Span**	**7 Span**	**8 Span**	**9 Span**	**10 Span**	**11 Span**	**12 Span**
1	4%	3%	2%	2%	1%	1%	1%	1%
2	12%	8%	6%	5%	4%	3%	2%	2%
3	20%	14%	10%	8%	6%	5%	4%	3%
4	28%	19%	14%	11%	9%	7%	6%	5%
5	36%	25%	18%	14%	11%	9%	7%	6%
6		31%	22%	17%	14%	11%	9%	8%
7			27%	20%	16%	13%	11%	9%
8				23%	19%	15%	12%	10%
9					21%	17%	14%	12%
10						19%	16%	13%
11							17%	15%
12								16%
	100%	100%	100%	100%	100%	100%	100%	100%

LEPA

Low energy precision application (LEPA) irrigation was developed in the 1980's on the water-short Texas High plains where deficit irrigation is prevalent and system capacities are low. The original concept combined double-ended socks and furrow dykes (small mounds or dykes in the furrows to trap small pools of water, preventing runoff and allowing infiltration to occur) although bubbler systems which drop water directly onto the soil surface are also available (Figure 5.5.3).

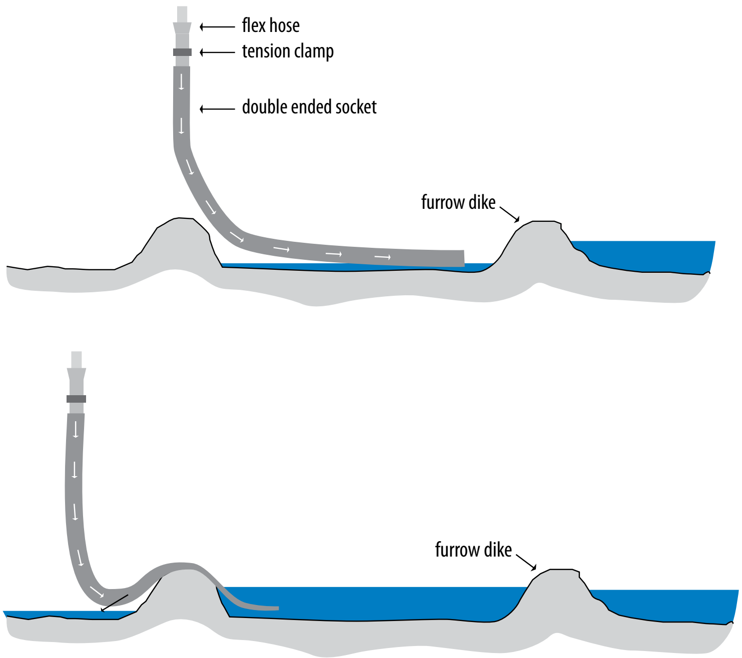
Figure 5.5.3. Emitter options for low energy precision application

(a) Drag sock

(b) Quadspray in bubbler mode

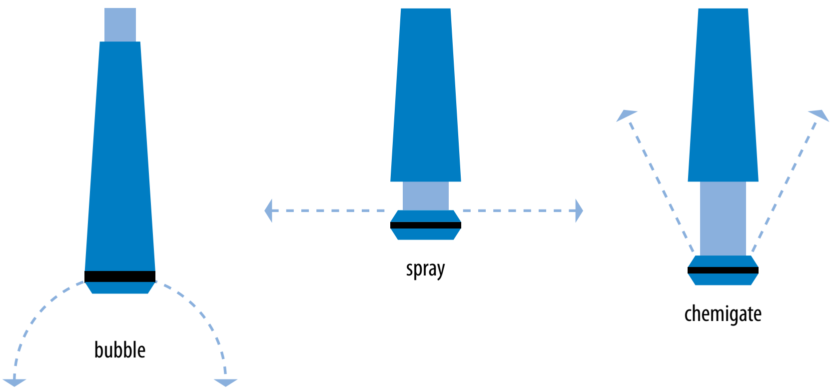
Both types of head are commonly suspended from the main pipe by flexible hose at either one or two crop row intervals. Drag socks come in both double and single ended sock options. Double ended socks are used in conjunction with furrow dykes, or tied ridge structures, to reduce the risk of washing these structures away (Figure 5.5.4). Bubbler units typically consist of either a "bubbler clip" attachment to a static plate sprinkler or a special "Quadspray" unit which has four operating modes that allow water to be either bubbled out in a low-pressure circular sheet, sprayed horizontally (germination mode), sprayed vertically upward (chemigation mode) or dribbled out directly from the bottom (Figure 5.5.5). Changeover from one operational mode to another only involves a click and twist rotation.

Figure 5.5.4. Operation of a double-ended LEPA drag sock in conjunction with furrow dykes



Source: New and Fipps 1990

Figure 5.5.5. Operational modes for Quadspray LEPA heads



Source: New and Fipps 1990

Drag socks are replaced with static plate sprinklers for crop germination and are positioned well above the soil surface to ensure good sprinkler overlap. It is important when using static plate sprinklers for germination that the sprinklers are placed at the height typically needed for the sprinkler throw. Often droppers have a connection at normal sprinkler height which is used for germination and an additional hose length is added when changing to LEPA mode so that the drag hose or bubbler outlet is close to the ground. Where any LEPA system is employed, there is both a time and labour requirement after crop establishment to allow changeover from the static plate sprinklers to the LEPA heads.

LEPA systems have very high average application rate (AAR – see below) because all of the nozzle flowrate is applied to a very small area of the soil surface. Even under the deficit irrigation and low system capacity conditions in which LEPA originally developed, furrow dyking was used to prevent surface water movement and runoff and allow time for water to infiltrate.

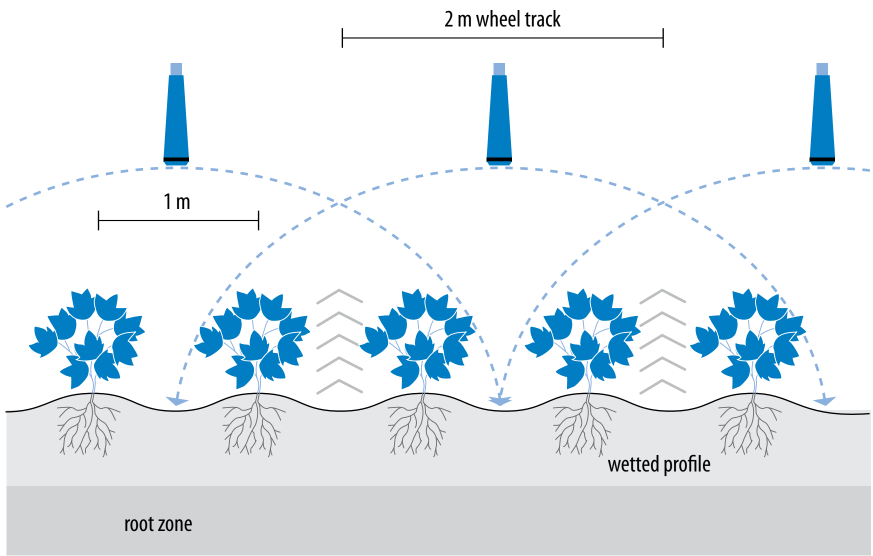
Despite LEPA being applied in Australia to high system capacity installations practicing full irrigation, furrow dyking has been uncommon and many growers prefer not to use LEPA socks because they tend to wear out due to the constant contact with the ground.

It is therefore not surprising that growers who install LEPA systems in Australia may have problems with water running along furrows and potentially resulting in runoff, wheel rutting or bogging. In cotton growing areas, natural soil cracks are commonly used instead of furrow dykes to retain water where it is placed, although this is not successful in all cases. Other practices such as stubble retention and rough, cloddy cultivation in furrow bottoms may be helpful for increasing the water retention capacity.

Sprinklers

Sprinklers are widely used on CPLM machines and are typically offered as standard fittings. While overhead and top-of-pipe sprinklers were common on older machines, newer machines are typically configured with over-crop sprinklers that hang down from the pipe (Figure 5.5.6).

Figure 5.5.6. Over-crop sprinkler irrigation



These over-crop sprinkler heads are available as either static or moving plate sprinkler heads. Static plates are a simple design with no moving parts. They consist of a nozzle which discharges water at a fixed plate which typically has a number of grooves in it (Figure 5.5.7). There are a range of configurations available to give different numbers of streamlets and different streamlet angles. Greater number of streamlets means finer drops are produced. Their simple design means they do not wear out quickly. The operating pressure is commonly 6 to 15 psi.

Figure 5.5.7 – A modern static plate sprinkler in operation (left) and an example of a 'triple deck' sprinkler with large nozzle and three levels of static plates.

Static plate sprinklers typically have the shortest throw distance of modern sprinkler types and their fixed streamlet pattern can result in high instantaneous application rates (IAR – see below). This may cause problems with erosion and soil crusting.

Such issues may be addressed by the use of moving plate sprinklers, by dividing the flow amongst a greater number of static plate sprinklers (with the use of spreader bars or boombacks) or by reducing nozzle sizes during early season irrigation whilst the soil is bare. Special static plate sprinklers with multiple plates also exist (e.g. Figure 5.5.7) which increase the number of streamlets, although these can be more prone to becoming clogged with trash.

Where static plate sprinklers are used for germination (e.g. LEPA bubbler systems) an alternate, smaller, nozzle is often used for the duration of the germination period. A dual nozzle clip is available to keep the alternate nozzle attached to the sprinkler body when not in use. As previously mentioned, it is especially important to employ the correct nozzles in the correct positions for centre pivot machines, and to adjust the pump appropriately for the reduced nozzle system flow rate

Moving plate sprinkler heads are newer technology. They operate at slightly higher pressures than static plate sprinklers (10 to 30 psi) and can generally be divided into three groups:

- Lower pressure, fast rotation (e.g. Spinners)
- Higher pressure, slow rotation (e.g. Rotators)
- Lower pressure, fast oscillation, multi-path (e.g. I-Wobb)

On moving plate sprinklers, the plate

moves due to the force of the water jet hitting the plate grooves. Moving plates produce a greater throw (wetted footprint), a more controlled droplet spectrum and a decreased IAR compared to the same number of static plate sprinklers. The larger wetted footprint also reduces average application rate which can be helpful in circumstances where runoff could be an issue. Slower rotating units produce moving streamlets whilst the spinning and wobbling variants produce a continuous shower of droplets (Figure 5.5.8)

Figure 5.5.8 - Rotating and wobbling plate sprinklers in action. Note the break-up of streamlets into droplets in both moving plate sprinkler types.

It is generally accepted that the replacement of older sprinkler technologies (both top-of-pipe and static head over-crop sprinklers) on existing CPLMs is a relatively simple and cost effective way of improving system performance. In general, the larger the number of streamlets produced by the emitter the smaller the droplet size and the lower the drop impact energy applied to the soil surface.

However, the lower the sprinkler head pressure, the larger the droplet size. Modern low-pressure sprinklers impart roughly 60% of the energy of old top-of-pipe high-pressure impact sprinklers (Kincaid, 1996). Hence, low pressures and large numbers of streamlets typically provide the best result in terms of reducing the instantaneous application rate, reducing the impact energy imparted to the soil and increasing the throw distance. These benefits typically minimise surface crusting and reduce run-off.

It is also relevant to briefly mention end guns, which are often fitted to centre pivots. They are viewed as a cheap way to increase the area covered or to attempt to irrigate the corners of centre pivot fields. They have a large gun with a large nozzle requiring high pressure to propel the water stream and make it break up for even application. Fitting these to a CPLM is putting together two different types of irrigation system, creating two different types of irrigation pattern, application rate and uniformity.

End guns normally apply less water than the rest of the system, and do so with poorer uniformity. The extra energy required to operate them negates one of the benefits of low pressure sprinklers. The usual result of using them is poorer crop performance compared to the rest of the system, higher operating costs and soil surface problems. It is inadvisable to fit these as it is usually false economy.

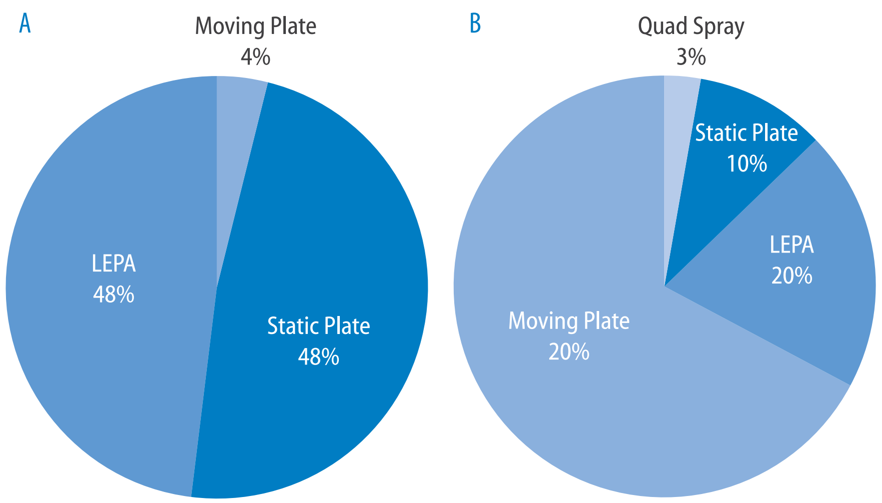
Trends in emitter use

Despite being developed in the 1980's, LEPA systems were not often used in Australia until they gained some interest in the cotton industry with a number of newly installed machines in the late 1990's and early 2000's. A 2001 study showed that by this time, 48% of growers using CPLM systems in the cotton industry used LEPA emitters (Figure 5.5.9). However a recent study (2011) using the same methodology found that only 20% of growers were using LEPA, although this subsequent study was limited to the Queensland Murray-Darling Basin and also included some grain irrigators.

Furthermore, the proportion of growers utilising moving plate sprinklers between these two studies increased from 4% to 67% and the use of static plate sprinklers decreased from 48% to 10%. Some of the growers who were featured in both studies had previously installed LEPA due to a range of previous concerns with sprinkler irrigation (such as potential effects on pollination or lint quality) which did not eventuate in practice and they have subsequently switched to sprinkler irrigation.

Sprinkler irrigation evaporation is another concern that may drive growers towards the use of LEPA systems, but modern sprinkler packages have been demonstrated to have very low evaporative losses, with maximums in the order of 0.5% (see below).

Figure 5.5.9 - Types of emitters used for in-crop irrigation in (a) 2001 and (b) 2011 (% of growers). Source: Review of CPLM systems in the QMDB



Infiltration under sprinklers and LEPA

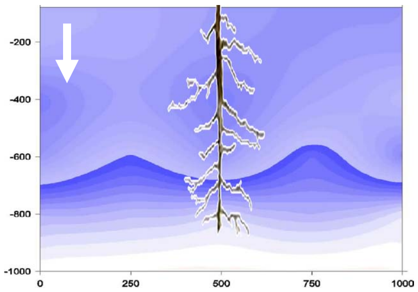
When choosing an emitter type, growers are often interested in understanding how water might infiltrate into the soil in their field. Whilst the specific circumstances of each field and irrigation application will differ, researchers at the National Centre for Engineering in Agriculture produced a number of two dimensional images of soil moisture changes under different soil type, deficit and emitter types to demonstrate broad trends.

Figure 5.5.10 includes a number of images demonstrating the change in soil moisture due to CPLM irrigation events in a range of conditions. Each image shows a a one metre transect of the plant row, from furrow to furrow, to a depth of one metre. The result is a one metre by one metre grid of soil moistre. An arrow indicates the furrow in which LEPA irrigation is applied (where applicable)

Each image shows the change in soil moisture from ten minutes before an irrigation event to ten minutes after the irrigation event. In each case, the intensity of blue colour indicates how much water has been added to the soil at that point, whilst white means no change in soil moisture and red means a decrease in soil moisture. As can be seen, some images show the plant continuing to use moisture at depth during the irrigation event whilst moisture is being added higher in the profile.

A range of scenarios were investigated, including cracking black and sealing red soils, both sprinkler and LEPA emitter types as well as a number of soil moisture deficits and irrigation application depths. Whilst the full range of results can not be included here, the patterns produced showed that water was rapidly redistributed through the profile in soils with cracks, even quickly moving through the plant line into non-watered furrows under LEPA irrigation. When the initial soil mositure deficit was low, irrigation water tended to stay in the upper soil layers as deeper layers were already moist and cracks were not evident. Infiltration under sprinkler irrigation on hardsetting or sealing soils was generally quite even and tended to infiltrate to the limit of existing moist soil.

Figure 5.5.10 – Change in soil moisture under a range of CPLM irrigation conditions from ten minutes before irrigation to ten minutes after irrigation. Blue colour indicates increase in soil moisture whilst red indicates a decrease in soil moisture. Arrows indicate furrow in which LEPA irrigation is applied.



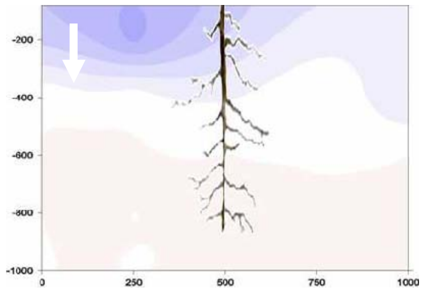
Black Cracking Clay

LEPA Bubbler

80 mm soil deficit

50 mm application

Irrigation water rapidly infiltrates the soil to depth, indicating flow through cracks. Soil in the non-watered furrow is also rapidly filled demonstrating the rapid redistribution of water throughout the profile.



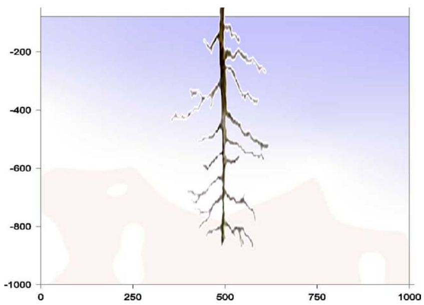
Black Cracking Clay

LEPA Bubbler

30 mm soil deficit

30 mm application

This irrigation was applied 24 hours after that in the previous image. Irrigation stays near the soil surface as the deficit was now much lower and the cracks were closed. Water still moves through the plant line to the non-watered furrow. Some extraction of water at depth.



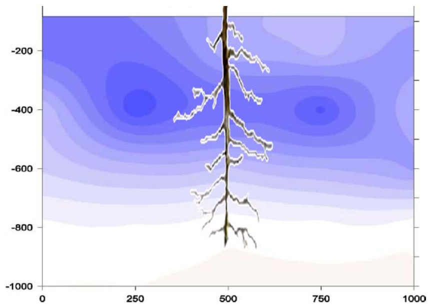
Black Cracking Clay

Sprinkler

90 mm soil deficit

26 mm application

Water infiltrates to a depth of 500 to 600 mm across the profile.



Red Hardsetting Soil

Sprinkler

50 mm soil deficit

24 mm application

Water infiltrates to a depth of around 600 mm, preferentially filling some drier areas that existed at around 400 mm

Presure Regulators

Pressure regulators are fitted on the drop tubes above the emitters. They are used to limit the maximum pressure at individual nozzles to aid in the control of:

- flow rate variation across the system length;
- desired droplet size;
- distribution uniformity; and
- sprinkler streamlet throw.

Variation in individual sprinkler pressure arises from variations in height due to terrain or emitter placement and pressure loss down the pipeline on the spans. It has become common practice to fit regulators to all machines. Whilst there are situations where pressure regulators may not be required on some systems, there use is common when very low pressure sprinkler packages (6 and 10 psi) are used.

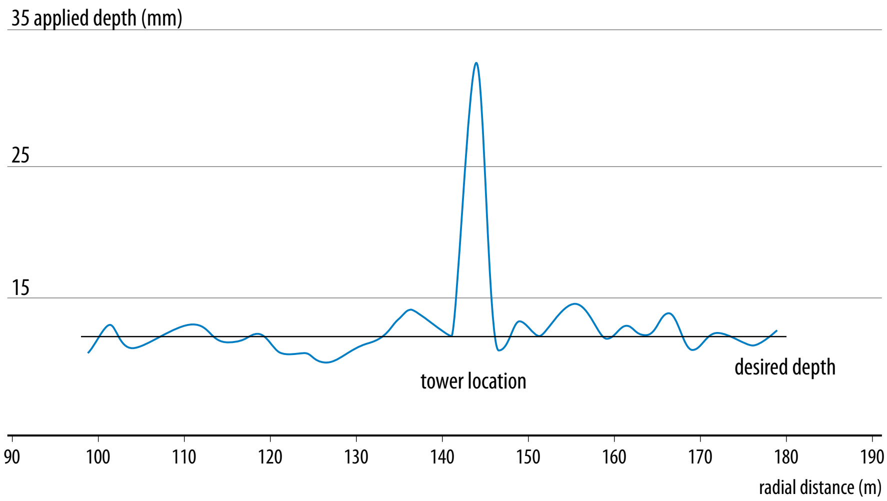
The system pressure above the pressure regulator at the worst-case situation (i.e. the emitter at the outer end(s) of the machine while at the highest spot in the field) should be (3 – 5 psi) higher than that specified on the pressure regulator to ensure the regulator operates correctly. Check that regulators are the correct pressure rating for the sprinkler package – it is common for a system to be designed with emitters operating at a specified pressure and to be supplied with incorrectly rated regulators.

Boombacks

Boombacks are used to suspend the emitters at a distance of 3 to 6 m behind the machine towers (Figure 5.5.11). These optional fittings are used to improve the uniformity of sprinkler application to the crop near the towers and to reduce the potential for irrigation water intercepted by the tower (Figure 5.5.12) causing either rutting or bogging. Where the machine is required to move in both directions, boombacks can be fitted to both sides of the tower with the appropriate set of emitters selected using either manual or automated valves. Alternatively, a single boomback mounted on a hinged fitting can be used and swung either side of the towers, depending on the direction of travel.

Figure 5.5.11. Fixed and swivel mounted boombacks for CPLMs 1 m

Figure 5.5.12. Field test results showing three times the normal amount of water being applied around the tower through interception of sprinkler water by tower structure



Source: Foley 2000

Tyres and wheel sizes

CPLMs represent a considerable investment in tyres and wheels, so growers should also ensure that they have the necessary equipment to re-inflate, replace or otherwise repair tyres on the machine. This typically involves having spare tyres, along with lightweight jacks and blocks.

Larger tyre sizes are sold as options to reduce wheel rut formation. Common tyre sizes for centre pivot and lateral move machines include 14.9′ × 24′, 16.9′ × 24′, 16.9′ × 28′ and 11.2′ × 38′. However, these sizes result in ground pressures for a wet 48 m span (weight ~ 3750 kg) with a 100 mm deep wheel rut of 12.9, 11.4, 10.8 and 14.6 psi respectively. Hence, while there are some differences in ground pressure associated with changes in tyre size, larger tyres do not generally reduce rutting as much as boombacks, which reduce the wetting of the wheeltrack area. Larger wheel and tyre sizes also increase loading upon gearboxes and drive trains. Tyre wheel combinations can also be purchased in sizes up to 18.4′ × 28′, 16.9′ × 34′ and 16.9′ × 38′. However, manufacturers do not normally like to supply these larger sizes because of the higher drive train loads involved.

High speed ratios are also sometimes sold as solutions to wheel rutting problems. However, high speed drive-train combinations may produce start-up torques that are greater than the design specification for the machine, leading to increased occurrences of motor burnout. Gearbox failures are also often the result of overloading the machine drive-train. Larger width tyres may result in tyre centrelines that overhang from the gearbox attachment points, thus increasing the risk of failure. Where larger and wider tyres are used, the power cable size and hydraulic lines should be increased in capacity to cope with the greater power requirements.

Guidance

Guidance is a critical component of lateral move systems which, unlike centre pivots, are not tethered at one end and are therefore able to move freely of their own accord. Historically, poor guidance has been one of the factors leading to increased labour requirements for lateral moves over centre pivot systems, although guidance systems have improved substantially in recent years and management problems are much reduced.

Lateral move equipment moves through a field using one of several types of guidance options:

Above-ground cable: a tensioned cable extended adjacent to the travel path of the cart is used to guide the system. One or two arms extending from the cart have sensors touching the cable. These sensors mechanically pick up movement by the cart away or towards the cable and signal the movement system to adjust accordingly. The cable must be straight and located, installed and tensioned with great accuracy. Weed control along the cable is important. Above ground cable may be located on any tower on the machine.

Below-ground cable: a buried cable that transmits a signal received by antennae attached to the cart or a span. The antennae allow sensing of movement by the machine away or towards the cable and signal the movement system to adjust accordingly. The cable must be located and installed with great accuracy. Buried guidance is normally mounted in the middle of the machine regardless of cart location.

Channel: where the LM is supplied by a channel, sensor arms extending from the cart have skid plates touching the inside of the channel. These sensors pick up the mechanical movement of the cart away or towards the channel and signal the movement system to adjust accordingly. The channel must be concrete lined and located and formed with great accuracy.

Small furrow: a separate small V-shaped furrow is formed along the length of the travel path to suit guidance arms extending from the cart. The arms move in the furrow as the cart moves, mechanically sensing any misalignment of the cart. Furrow guidance may be located on any tower on the machine.

GPS: uses GPS sensors to determine deviation from the correct travel path. This requires the use of high resolution GPS units and careful programming of the travel path. GPS guidance eliminates maintenance issues associated with mechanical guidance options and may improve precision of lateral moves. In Australia, coastal areas seem to work well but further inland more satellite outages seem to occur. For the immediate future, GPS is more likely to be used for monitoring machine position rather than guidance.

Automation

Control panels vary in complexity depending on requirements. Where necessary, all functions can be manually controlled. Features that are commonly available include machine remote control using either computers or mobile phones with voice feedback and programs to apply varying amounts of water over different periods. It is possible to program the machines to stop where required or vary the application across the field. For lateral move machines, it is possible to progressively apply lighter amounts of water and then to reverse direction at the end of the field, applying increasingly larger amounts of water.

Pressure switches are commonly incorporated to stop pumps when pipes burst (that is, on low pressure) or to start the machine moving when water pressure builds up. Hydraulically driven machines often employ electric over hydraulic controls to perform the more complex tasks of automation. Automation is essential to take full advantage of the CPLMs' capacities. While automation may increase the machine complexity, it can substantially reduce the time involved in management and provides the level of control required to maximise the return on investment.

Fertigation and Chemigation

Fertigation and chemigation using CPLMs can be conducted in two distinct ways. Chemical can be injected into the irrigation water in the main pipe for distribution through the emitters with the water. Products that can be distributed in the irrigation include fertilisers, herbicides, insecticides, and fungicides. Alternatively, chemigation can be conducted using a separate system of distribution pipes with spray heads suspended underneath the CPLM truss rods to enable the application of chemical with or without irrigation water.

Fertigation is widely practiced by CPLM operators and is covered further in WATERpak Chapter 5.8.

Measuring the performance of CP & LM machines

The three most important measures of CPLM performance are application rate, uniformity of application and application efficiency. This section explains the importance of each measure and outlines the design and management factors that influence the relevant machine performance variable.

Application rate

Three measures of the application rate are important: the system capacity, the average application rate (AAR) and the instantaneous application rate (IAR). These measures differ primarily in the time scale being considered: system capacity measures are commonly reported as volumes applied per day or week, the average application rate reported as volumes per hour, and instantaneous rates reported as volumes per second.

System capacity: The system capacity of a CPLM machine is the average daily flow rate of water pumped by the machine divided by the area of that irrigated crop field. It is expressed in the units of millimetres per day, so that it can be directly compared with the peak crop evapotranspiration rate. Alternative units for system capacity would be in ML/ha × 10^2/day (that is, ML per hundreds of hectares per day). System capacity is the maximum possible rate at which the CPLM can apply water to the chosen area of irrigated field. It is **not** the amount of water that the machine applies per irrigation pass.

Dealers and manufacturers commonly use system capacity for their calculations and their assumption is that the pump is running for 24 hours a day, seven days a week, providing 168 hours a week pump running time.

The system capacity (in millimetres per day) is calculated by converting the CPLM's pump flow rate into litres per day, and dividing by the irrigated field area in square metres. Remember, 1 litre over 1 square metre equals

1 millimetre depth of water applied. Alternately, growers can calculate the system capacity (mm/day) by taking the megalitres per day pumped onto the irrigated field and dividing by the irrigated area in hundreds of hectares.

$$\text{System Capacity (mm/day)} = \frac{\text{Average daily pump flow rate (L/day)}}{\text{Area Irrigated (m}^2\text{)}}$$

The design and management issues associated with the system capacity are often not well understood by Australian growers using these machines and account for many of their perceived failures. System capacity is discussed in further detail in the next section

Average application rate: The average application rate (AAR) is the average depth of water applied to the irrigated field during the irrigation. The AAR is calculated by dividing the emitter flow rate (in litres per hour) by the wetted soil surface area (in square metres). The AAR is normally reported in millimetres applied per hour, to allow for a direct comparison with soil infiltration rates.

AAR is altered when emitter wetted area or flow rate is changed. The wetted

$$\text{AAR} = \frac{\text{Nozzle Flow Rate (L/hr)}}{\text{Wetted Soil Area (m}^2\text{)}}$$

area is affected by sprinkler height, wind, and sprinkler impact plate changes. Nozzle pressure, nozzle size and sprinkler spacing affect individual sprinkler flow rates.

The introduction of low-pressure fixed sprinkler plate technology in the 1960s and 1970s resulted in increases in AARs because the area wetted by the sprinklers was smaller than that with the previous higher-pressure sprinklers. However, the more recent development of rotators, wobblers, spinners and other moving plate sprinklers have resulted in a substantial decrease in AARs due to the larger throw and greater average droplet diameter of these emitters.

For centre pivot machines, the highest AAR is found at the outer end of the machine. AAR will always be greatest at the outer ends of centre pivots equipped with only one type of emitter and nozzle, as individual emitter flow rates increase in response to the larger annular area irrigated. The AAR of lateral move machines will be lower than the AAR at the outer ends of centre pivots. Individual emitter flow rates on a lateral move will be much smaller than an emitter located on the outer end of a centre pivot that has a similar irrigated area and managed system capacity.

Considerable research in the USA has been conducted upon the common mismatch of AAR and soil infiltration rates at the outer ends of centre pivot machines. For example, Scherer (1998) showed that sprinklers that throw to a radius of 10 metres, sited on the end of a 400 metre long centre pivot, produce average and peak application rates in the order of 40 and 50 mm/h, respectively. When these AARs are compared to the 5 mm/h average infiltration rates common for many clay soils, it is inevitable for the resulting excess water to be temporarily stored in surface roughness or run-off. This is supported by a range of work which suggests that the AAR associated with low pressure sprinklers on the outer ends of centre pivots will commonly exceed the infiltration rate of all soils except sands (for example, Kincaid et al. 2000; King and Kincaid 2001). Other options to reduce surface run-off under these conditions include retaining crop stubble, using spreader bars to increase separation between emitters and using long throw spray emitters.

Instantaneous application rate: The instantaneous application rate (IAR) describes the rate at which water is applied by an individual streamlet from an emitter head to a very small area of irrigated field (for example, hundredths of a square metre). The time scale under consideration for determination of IAR is in the range of seconds and the IAR is typically 1.3 to 1.5 times greater than the AAR (Kincaid et al. 2000). High IARs are commonly recorded where streamlets from static plate sprinklers impact upon a small portion of irrigated field during the stop cycle of electrically driven centre pivots. However, there will be zones of high IAR within the wetted area of every sprinkler pattern.

IARs under CPLMs are rarely measured in the field. However, the genesis of larger run-off issues is contained in this small area and time scale. Puddling of the soil surface begins from the impact of the streamlets, and is rapidly followed by soil surface sealing through the rearrangement of the destroyed soil crumbs. Most CPLMs in this country are equipped with rotating, spinning and oscillating plate sprinklers that overcome the high IAR by not having individual streamlets that apply water to any one point. Irrigator concern regarding droplet impact energy (Stillmunkes and James 1982) creating soil crusting issues during germination has led manufacturers to develop specific sprinklers to help germination.

Uniformity of application

Uniformity of application refers to how evenly the irrigation water is applied across the field. In fields not watered uniformly, some parts will be irrigated to the desired depth, while other parts will be either under- or over-irrigated. These non-uniformities lead to yield variation across the irrigated area, resulting in differences in economic return for different portions of the field (Solomon 1988). The factors that contribute to non-uniformity include:

- emitter spacing, nozzle operating pressure, and emitter configuration
- nozzle size and selection with location along machine
- nozzle height, angle and wear
- machine movement including step size and its consistency
- flow rate variations due to discontinuous end-gun operation, and variations in pump duty, and
- run-off from high application rates.

Large nozzle gun sprinklers, which are commonly positioned on the ends of CPLMs, are also often responsible for the poor uniformity performance of application (Molle 1999). Poor uniformity around wheel towers on CPLMs is also a common problem, as growers and distributors often employ inappropriate techniques to reduce wheel bogging, resulting in lower uniformity and application rates in the vicinity of the wheel towers.

As CPLMs do not irrigate all parts of the field at any one instant, they must apply the same depth of water along their travel path and machine length to irrigate uniformly. This requires a different evaluation methodology from that employed on static sprinkler systems. Measurements are commonly taken along one or two transects across their travel path. However, this always results in an underestimate of the uniformity, because no measure of the variation along the direction of travel is obtained. To adequately determine uniformity across the whole field, monitoring is necessary along the full travel path of the machine.

While standards for testing the spatial uniformity are available (for example, ISO11595; ASAE S436) there is still some debate over the appropriateness of the methodology employed in these standards. The dependence of uniformity measures upon sampling spacings (for catch-can layouts) has been discussed by Smith and Black (1991). On the basis of sampling theory, they recommended that catch can spacings should be of the order of ¼ of the sprinkler spacing (Smith 1995). Bremond and Molle (1995) likewise analysed catch-can spacing and determined that assessment errors could be minimised and catch-can spacings maximised when 5 m spacings were used for CPLMs with sprinkler wetted diameters of 20 metres.

Two coefficients are commonly used to express the uniformity of irrigation systems – distribution uniformity (DU) and uniformity coefficient (Cu). The DU is an empirical index that is calculated as the ratio, expressed as a percentage, of the mean of the lowest one-quarter of applied depths and the mean of all applied depths:

$$\text{DU (\%)} = \frac{\overline{x}_{lowerquarter}}{\overline{x}} \times 100$$

where $\overline{x}_{lowerquarter}$ equals the mean of the lowest 25% of individual catch-can depths and $\overline{x}$ equals the mean of all individual catch-can depths. The uniformity of application for solid set impact sprinklers has traditionally been considered acceptable if the calculated DU is greater than 75%. However, Bremond and Molle (1995), Heermann (1991) and Yonts et al. (2000b) have suggested that DU should be greater than 90% for CPLMs to be considered to be performing well.

The Uniformity Coefficient (Cu) was first proposed by Christiansen (1942) and is defined as:

$$C_u = 100\,(1 - \frac{M}{\bar{x}})$$

where M is the mean absolute deviation of the applied water depths $\bar{x}_i$ (or catch-can depths from sampling grid) and is given by :

$$M = \frac{\sum |\bar{x}_i - \bar{x}|}{n}$$

where $\bar{x}$ is the mean applied depth and n is the number of measurements. For systems that have a considerable variation in uniformity, there will be large variations from the mean and the coefficient will decrease. Solid set sprinkler systems that have a Cu less than 86% would typically be viewed as under-performing while CPLMs would be expected to have a Cu greater than 90% to be considered acceptable.

Heermann and Hein (1968) proposed a measure of application uniformity that should be used specifically for centre pivot machines. In this measure, the applied depths are weighted according to their radial position along the length of the machine, to allow for the different annular area represented by each depth. The modified Heermann and Hein (1968) coefficient of uniformity can be written as:

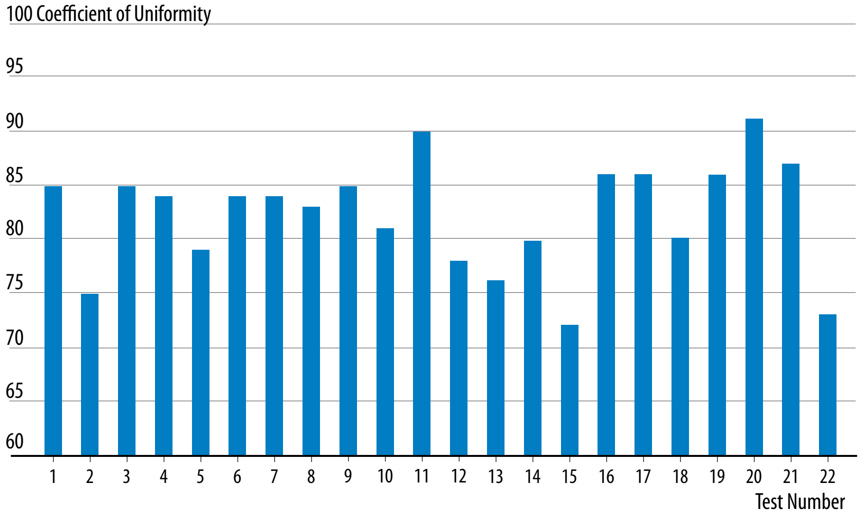
$$C_u = 100\left[1.0 - \frac{\sum_s S_s\,|D_s - \bar{D}|}{\sum_s D_s S_s}\right]$$

where D_s is the applied water depth for one collector position, $\bar{D}$ is the average applied water depth for all collectors, and S_s is the distance to equally spaced collectors.

Marek et al. (1986) and Bremond and Molle (1995) introduced other areal weighted uniformity coefficients specifically for centre pivot machines. Both of these methods use the square of the differences from the mean, rather than mean deviation as used by Heermann and Hein (1968). These methods emphasise any significant deviations from the mean and are useful in highlighting the poor performance of broken or blocked emitter nozzles. A number of researchers (for example, Heermann 1994; Smith 2000) have also suggested that representing the irrigation variation using a cumulative irrigation depth distribution curve may better describe the performance of an irrigation system than the use of a simple coefficient.

Figure 5.5.13 summarises the C_{U-HH} for 22 recently evaluated centre pivot systems, most of which were less than 3 years old. Despite the fact that such systems should be expected to have high uniformity, the average C_U was 82% and only two of the systems achieved the benchmark uniformity of 90% mentioned above. Such results reinforce the importance of performance measurement, even for new systems.

Figure 5.5.13 – Uniformity of 22 centre pivot systems. Few were able to reach the benchmark performance level of 90%. (Smith and Jessen, 2006)



Application efficiency

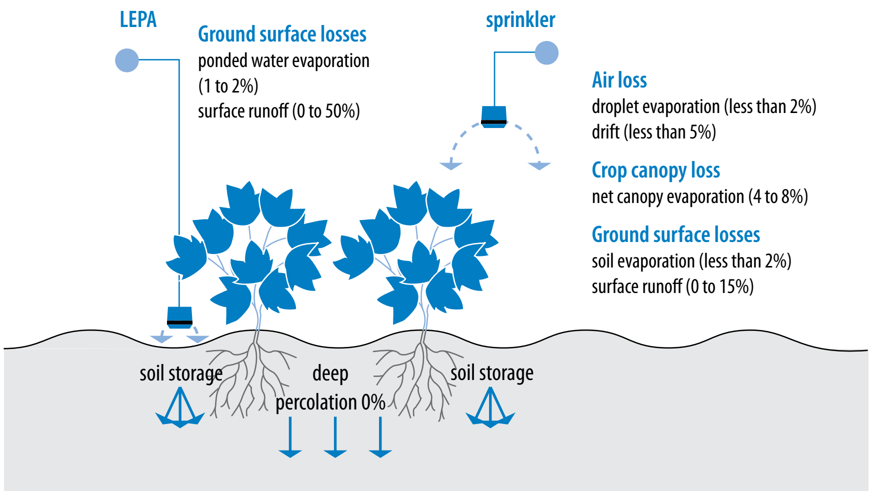
The **application efficiency** (E_a) is a measure of the losses associated with applying water to a field. It is calculated as the ratio, expressed as a percentage, of the volume of irrigation water stored in the root zone divided by the volume of water supplied to the field inlet (IAA 1998). The loss mechanisms that decrease application efficiency for CPLMs include:

- sprinkler loss of fine water droplets
- evaporative losses from either the soil surface or plant surfaces
- run-off from the irrigated field; and
- deep drainage.

As with other forms of irrigation, run-off and deep drainage are most commonly associated with poor management and system operation. However, wind drift and evaporative losses are strongly influenced by emitter selection, nozzle size, operation pressures, and emitter location in relation to the crop canopy and weather conditions.

Evaporative losses are not well understood by Australian growers using irrigation. Drift and evaporation losses of sprinkler droplets (Figure 5.5.14) using a typical CPLM sprinkler configuration (nozzle pressure=138 kPa, nozzle diameter=4.7625 mm) are commonly reported as less than 5% and rarely greater than approximately 8%, even under extreme weather conditions (relative humidity = 10%, dry bulb temperature = 43°C, wind speed = 19 km/h, for example, Frost and Schwalen 1960). Similarly, evaporation losses from the crop canopy surfaces may be as small as 1% to 2% (New and Fipps 1995; Yonts et al. 2000a) and are commonly reported as less than 8% (Schneider and Howell 1999). Hence, moving the emitter into or below the crop canopy may not necessarily increase application efficiency dramatically and may result in greater run-off water losses due to the increased IAR associated with the smaller wetted area.

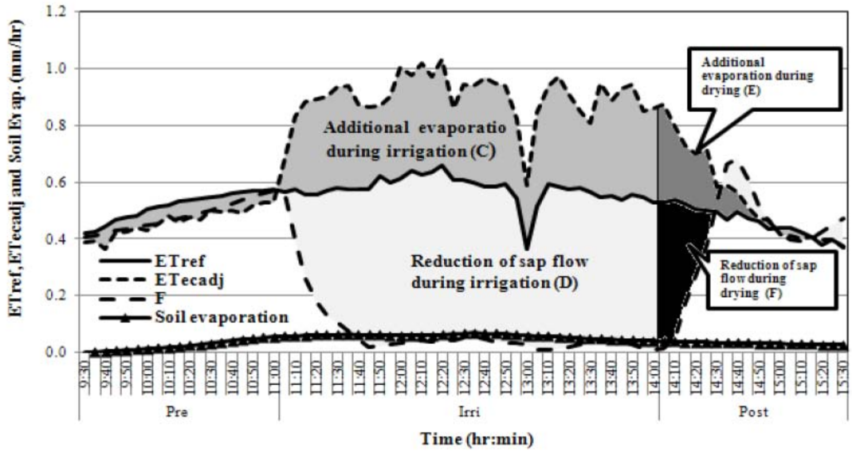
Figure 5.5.14. Illustration of the water loss pathways for LEPA and sprinkler application methods under CPLMs



Source: from Schneider 1999

Sprinkler evaporation is best calculated using equations for the transient transfer of heat to water vapour away from freely falling water droplets, as developed by Kinzer and Gunn and reported by Heermann and Kohl (1983). Further, Heermann and Kohl (1983) correctly state that not all canopy and soil evaporation should be considered a loss, as the evaporating water reduces the transpirative demand of the crop and decreases the crop water requirements, therefore fulfilling the primary function of irrigation; that is to supply water to the crop. This has been demonstrated under Australian conditions by Uddin et al. (2012) who measured the additional evaporation during sprinkler irrigation as well as the simultaneous reduction in crop transpiration (Figure 5.5.15).

Figure 5.5.15 – Additional Evaporation and reduced transpiration measured during sprinkler irrigation (Uddin et al. 2012)



This has also been supported by experimental data from an extensive energy balance experiment conducted in Texas (Thompson et al. 1997). The data from a lateral move irrigation machine, equipped in separate sections with both top of pipe impact sprinklers and grooved static plate sprinklers on droppers, records 0.053 mm and 0.055 mm of droplet evaporation for impact and static plate sprinkler, respectively. This represents less than 0.25% of the 25 mm irrigation applied. The conditions of the test day during the measured irrigation event included dry bulb temperatures of 31°C and average wind speeds of 7.5 m/s. Maximum droplet evaporation rates were 0.04 and 0.14 mm/hr for the impact and static plate sprinklers, respectively, during the test period.

Schneider (2000) records other work detailing plant canopy evaporation as typically less than 5%, but soil evaporation on bare earth where there is no beneficial gain will potentially lose up to 10 mm in the first day after irrigation with a fully wet soil surface.

In summary it can be stated that modern low pressure, static plate and moving plate sprinklers have application efficiencies up to 95%. LEPA socks and bubbler emitters have been found to have application efficiencies up to 98% where surface run-off is well controlled. However, up to 50% runoff has been found (Schneider, 2000) where LEPA systems are operated under adverse conditions without furrow dyking.

Designing the system capacity of CPLMs

System capacity is the most important design parameter for CPLM machines in the Australian cotton industry. Many machines installed in Australia in the past do not have a system capacity large enough to ensure cotton crop success. The problem of low system capacity has been the single greatest reason for the low uptake of CPLMs in Australia, and only if they can supply water onto irrigated cotton fields at a rate great enough to cater for peak crop evapotranspiration rates can they succeed in the Australian cotton industry.

The highly variable climate in which the Australian cotton industry operates means that timely and beneficial rainfall cannot be relied upon to help irrigation systems during peak crop water requirement. No benefit can then be allocated to rainfall supplementing irrigation during that period when the crop most requires water and is not included in any of the following analyses.

This discussion assumes that growers have an adequate volume of water allocated for the irrigated area underneath their CPLM. Understanding your water resources is important, and other authors in WATERpak have addressed this issue.

Calculating the system capacity of your CPLM

To calculate your system capacity, take the flow rate of water pumped by your CPLM installation and divide by the area of crop that the CPLM will cover in any one cotton season.

$$\text{System Capacity (mm/day)} = \frac{\text{Average daily pump flow rate (L/day)}}{\text{Area Irrigated (m}^2\text{)}}$$

Example 1: LM system capacity

A lateral move is capable of pumping 300 litres per second onto 180 ha in a day – what is the system capacity?

Volume applied (L/day) = 300 L/s × 60 s/min × 60 min/hour × 24 hours

= 25 920 000 L/day

Area irrigated (m^2) = 180 ha × 10000 m^2/ha

= 1 800 000 m^2

System capacity (mm/day) = volume applied (L/day) ÷ area irrigated (m^2/day)

= 25 920 000 L/day ÷ 1 800 000 m^2/day

= 14.4 L/m^2

≈ 14.4 mm/day (as 1 L/m^2 = 1 mm)

Alternatively, divide the CPLM flow rate in ML/day by the area in hundreds of hectares, that is, 25.92 ML/day divided by 1.8 hundred hectares equals a system capacity 14.4 mm/day.

Example 2: Large lateral move capacity

A large lateral move runs along a supply channel that is 6600 metres long. The overall length of the lateral move machine is 1008 metres and the length of irrigated field underneath the lateral move is 984 metres. The pump flow rate for this lateral move is 300 L/s or 25.92 ML/day. If two 800 metre long fields, back to back, are used to grow cotton in one season, then what is the system capacity?

Volume applied (L/day) = 300 L/s × 60 s/min × 60 min/hour × 24 hours

= 25 920 000 L/day

Area irrigated (m^2) in a single cropping season = 984 m × 800 m × 2 fields

= 1 574 400 m^2

System capacity (mm/day) = volume applied (L/day) ÷ area irrigated (m^2/day)

= 25 920 000 L/day ÷ 1 574 400 m^2/day

= 16.46 L/m^2

≈ 16.5 mm/day (as 1 L/m^2 = 1 mm)

Example 3: CP system capacity

Calculate the system capacity of a 496 metre long centre pivot, that is, 10 × 48 m spans + 16 m overhang with a pump flow rate of 141 litres per second

Volume applied (L/day) = 141 L/s × 60 s/min × 60 min/hour × 24 hours

= 12 182 400 L/day

Area irrigated (m^2) = π × radius^2

Where, π = 3.14

radius = 496 m

Therefore, Area = 3.14 × 496 m × 496 m

= 772 490 m^2 or 77.249 ha

System capacity (mm/day) = volume applied (L/day) ÷ area irrigated (m^2/day)

= 12 182 400 L/day ÷ 772 490 m^2/day

= 15.77 L/m^2

≈ 15.8 mm/day (as 1 L/m^2 = 1 mm)

Alternatively, the flow rate, 12.1824 ML/day divided by 0.77249 hundred hectares = 15.77 ML per hundred hectares per day = 15.77 mm/day.

This is how to calculate the system capacity of CPLMs. It is a very important design parameter and is the maximum possible flow rate the machine can apply onto the irrigated area. Remember this is not the amount of water applied per irrigation pass.

Managing CPLM system capacity

The system capacity is the maximum possible flow rate that the CPLM can apply to the area of an irrigated field. The system capacity of a CPLM is reduced considerably in the real world by the number of hours that the pump is turned off during any given irrigation cycle. The amount of time the pump is running during any irrigation cycle is called the **pumping utilisation ratio (PUR)**.

The pumping utilisation ratio can be calculated from the average number of pumping hours per day divided by 24 (or divide the total hours of pumping over a 10-day period by 240 hours, let's say 204 ÷ 240 = 0.85). Remember to take into account the non-irrigating time necessary for any pesticide spraying with over-crop sprinklers and the dry travel time of the CPLM that you think that you may need.

System capacity is further reduced by losses that occur when the water travels from the nozzle on the machine into the crop root zone. This ratio of the water that actually makes it into the crop root zone divided by the total amount of pumped water is called the **application efficiency** (see earlier discussion). For LEPA systems, choose an application efficiency of 0.98, and for modern over-crop sprinkler systems choose a value of 0.95.

$$\text{Managed System Capacity (mm/day)} = \text{Design System Capacity (mm/day)} \times E_a\,(\%) \times \text{PUR}\,(\%)$$

As an example, a grower running a CPLM pump for 204 hours throughout a 10 day period during the peak crop water use period, using a well-tuned over-crop sprinkler system, would be able to irrigate at a rate of 0.85 × 0.95 = 0.81 of the system capacity.

In a worst case scenario you might have a system capacity of 14 mm/day, but if the pump only ran for 0.75 of the time, even with a LEPA system, then on average 10.5 mm/day would be applied into the crop root zone.

Remember that these system capacity values have nothing whatsoever to do with the amount of water applied by the CPLMs during each irrigation pass. The amount of water that is applied per pass is governed by the pump flow rate and the amount of time that the machine takes to complete one irrigation pass of the complete irrigated area. Just as a constant flow rate boomspray operator would reduce speed to apply a greater amount of water to the field, so too is the average speed of a CPLM reduced to apply more water per pass.

For example, a centre pivot grower using good over-crop sprinklers with a system capacity of 14 mm/day, decided to set the machine speed so that the centre pivot took 2.5 days to irrigate the full circle, and then stop the machine for 0.5 day before restarting the machine. Under this management, the centre pivot would apply 14 mm/day × 2.5 days/pass × 0.95 = 33.25 mm for that irrigation.

Example 4: Managed system capacity

A large lateral move is designed with LEPA socks and a pump flow rate of 300 L/s with an irrigating width of 984 metres. The pump will run for 8.5 days out of 10 during peak crop evapotranspiration period. This downtime of 1.5 days includes time where the machine is being shifted across ends of fields or returning to the dry end of the field, or while aerially sprayed pesticides are being applied to the crop. The LEPA lateral move runs across two fields that are 900 metres long for a total cropped field length of 1800 metres. The managed system capacity (the average amount that the machine will apply into the crop root-zone per day) will be:

Managed System Capacity

$$= \frac{\text{volume applied(L/day)} \times \text{pumping utilisation ratio} \times \text{application efficiency}}{\text{area irrigated (m}^2\text{)}}$$

$$= \frac{300 \text{ L/s} \times 3600 \text{ s/h} \times 24 \text{ hrs/day} \times 0.85 \times 0.98}{984 \text{ m} \times 1800 \text{ m}}$$

$$= \frac{21\,591\,360 \text{ L}}{1\,771\,200 \text{ m}^2}$$

$$= 12.19 \text{ L/m}^2$$

$$\approx 12.2 \text{ mm/day}$$

Alternatively, the 300 L/s equals 25.92 ML/day, and calculating how much water this will apply into the root zone per day over the 177.12 ha is given by 25.92 ML/day × 0.85 × 0.98 divided by 1.77 hundred hectares = 12.19 mm/day.

Choosing a system capacity for your CPLM

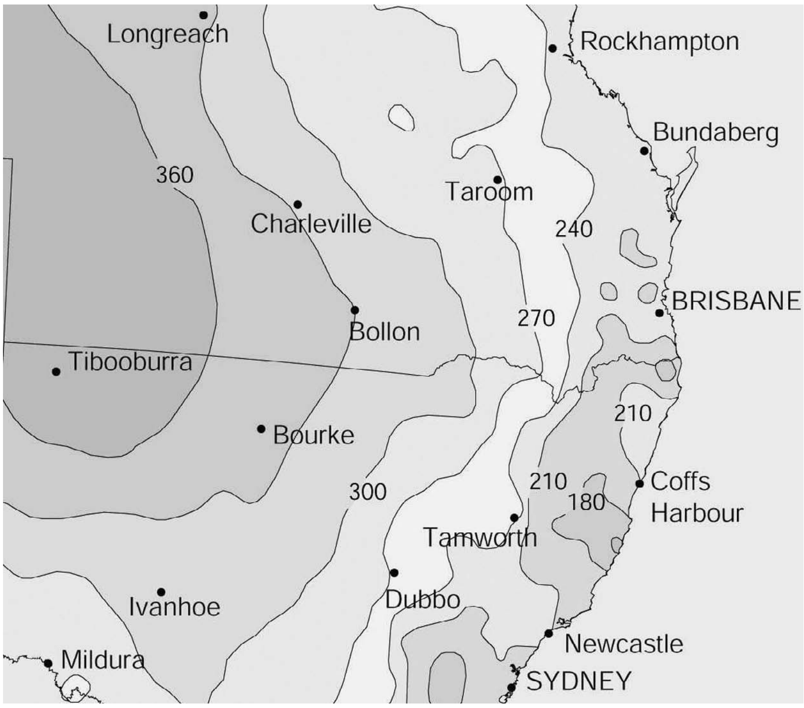
A common question raised by many cotton growers who are contemplating the installation of CPLMs is "What System Capacity should my CPLM have on my field?" The answer is that the system capacity should be sufficient to meet the crop water requirements for an extreme ET event.

Step 1 – Determine local peak potential evapotranspiration

A process for choosing a suggested CPLM system capacity has been developed utilising the evapotranspiration maps of Australia developed by the CRC for Catchment Hydrology and the Bureau of Meteorology under their technology transfer program (Wang et al., 2001) (see WATERpak chapter 2.8).

The point potential ET map for January (Figure 5.5.16) gives the period of greatest potential ET and also coincides with the period of greatest crop water requirement for cotton and most summer crops. If only winter crops are to be grown, a map for an appropriate month of the winter growing season could be used. Find your location on the map and determine the monthly ET by interpolating between the closest ET lines. Note that the mapped lines of equal potential evapotranspiration are in incremental steps of 30 mm per month.

Figure 5.5.16. January monthly average point potential evapotranspiration map for Australia's existing cotton-growing regions



Source: Wang et al. 2001. Originally developed by the CRC for Catchment Hydrology and Bureau of Meteorology, based on data from 1961 to 1991.

Table 5.5.3 – Crop coefficients (K_c) for common crops in sub-humid and arid environments (FAO Paper No. 56)

Crop	Wind Speed Relative Humidity (min)	≈ 2 m/sec 45%	≈ 6 m/sec 25%
Maize	mid-season	1.15	1.35
	maturity	1.05	1.1
Sorghum	mid-season	1.1	1.3
	maturity	0.55	0.55
Cotton	mid-season	1.2	1.35
	maturity	0.65	0.7
Soybeans	mid-season	1.15	1.25
	maturity	0.5	0.45
Oats	mid-season	1.15	1.3
	maturity	0.25	0.2
Wheat	mid-season	1.15	1.25
	maturity	0.3	0.2
Lucerne	after cutting	0.4	0.3
	between cuts	0.95	1.05
	ready to cut	1.2	1.3
Pasture	after grazing	0.4	0.5
	between cuts	0.85	1.05
	ready to graze	1.05	1.15

Step 2(a) – Determine system capacity for cotton

For cotton crops, a calibration factor has been derived from the system capacities of CPLMs across the cotton industry which can be applied to the figure obtained from the January map. The calibration factor takes into account the conversion of the monthly average value to the more useful 3 day peak ET_c value and assumes a pumping utilisation rate of 0.85 and the use of a LEPA system with an application efficiency of 0.98. If you wish to use other values for PUR and Ea, you may be able to adjust the value obtained from this step or alternatively follow the extended process below.

Once you have obtained your monthly figure from the map in Figure 5.5.16, divide this value by the cotton industry system capacity calibration factor of 21.5. The resulting number will be in millimetres per day, and is a starting point for grower's decisions regarding the appropriate system capacity for their CPLM design. If growers are concerned about the particular value they calculate, consult appropriately skilled irrigation professionals.

For example, a cotton grower wishes to install a centre pivot at Bollon, which lies on Figure 5.5.16 at the 330 mark. Divide 330 by 21.5 and the suggested System Capacity is 15.3 mm/day. This would be the System Capacity a grower would install when the pumping utilisation ratio is 0.85 and the application efficiency is 0.98.

If you are growing cotton and this process suits your requirements, you may finish at this point.

Step 2(b) – Modify the ET estimate for other crops

Alternatively, crop coefficients may be used to estimate the peak crop water use from the point potential ET map. Crop coefficients (K_c) developed for use with the Penman-Monteith equation relate a range of crops to a standard reference crop as well as taking into account the stage of crop growth. They are discussed in more detail in WATERpak Chapter 2.1.

It should be noted that these crop coefficients were derived to suit the Penman-Monteith method and were NOT intended for use with other methods such as this one. However, for planning a centre pivot or lateral move system, experience has shown that this process gives a reasonable estimate in lieu of an alternative approach. If better information is available for your region and conditions, be sure to use this.

The relevant crop coefficient can be obtained from Table 5.5.3 or WATERpak Chapter 2.1. To determine the peak daily water use, take the monthly point potential value from the map, divide by the number of days in the month and multiply by the relevant crop coefficient. This will give the value that the managed system capacity will need to satisfy.

Step 3 – Determine system capacity for other crops

Once you have modified the map ET for your relevant crop, you will need to take account of your predicted pumping utilisation ratio and application efficiency to determine the system capacity required. If you are using the cotton calibration factor approach in Step 2(a), these factors have already been accounted for within the calibration factor. You should not mix the two methods.

By rearranging the formula for managed system capacity presented previously, we can determine the design system capacity as:

Design System Capacity = Managed System Capacity ÷ PUR ÷ Ea

Because the managed system capacity needs to equal the peak crop water use, we can substitute this value in the equation above.

For Example:

Using the same example system as in Step 2(a) – a system for irrigation of cotton in Bollon, Qld. The peak ET month is January. From the map, point potential ET for Bollon is 330 mm. From Table 5.5.3, the crop coefficient for cotton for sub-humid regions is 1.2. The predicted pumping utilisation ratio is 0.85 and the system will use LEPA with a predicted application efficiency of 0.98

Daily ET for January = 330 ÷ 31 = 10.6 mm

Convert to peak crop water use = 10.6 × 1.2 = 12.8 mm/day

Determine design system capacity = 12.8 ÷ 0.85 ÷ 0.98 = 15.3 mm/day

Therefore, this system requires a design system capacity of 15.3 mm per day, the same as obtained using the cotton calibration factor in Step 2(a).

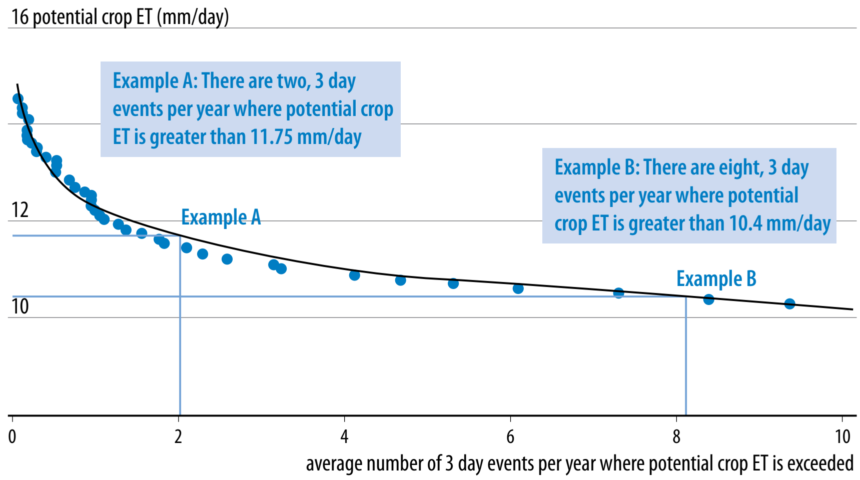
How does your design system capacity compare to a 3-day peak crop evapotranspiration rate?

In trying to understand whether or not a particular system capacity for a CPLM will adequately cater for the peak crop water requirements of a fully grown cotton crop, consider the evapotranspiration rates that would be likely to occur in any given crop growing season at a particular location.

If we were to undertake an analysis of the evapotranspiration for the St George region, the chances of having a 3-day average potential crop ET value greater than a certain size would look like the information detailed in Figure 5.5.17. When growers choose a certain system capacity for a CPLM installation in the St George region, for example, they are essentially choosing the number of days per year where the potential crop ET will be greater than the chosen system capacity of the CPLM installation. The nature of potential crop evapotranspiration is such that there is always the possibility in any year of a number of the days where high evaporation occurs.

The number of days per year where potential crop evapotranspiration is greater than the rate at which water can be supplied by the irrigation system needs to be reduced by choosing CPLM system capacities capable of handling these extremes. It does not matter how large a CPLM system capacity you choose, there will always be a day where peak crop evapotranspiration is greater.

Figure 5.5.17. Recurrence of 3-day peak crop evapotranspiration rates for the St George region



From the X-axis, consider the number of times per year where corresponding potential crop ET will be exceeded and then choose your own appropriate CPLM system capacity.

Understanding how many extreme 3-day peak crop evapotranspiration events per year will occur allows growers to determine their own level of risk in relation to their chosen CPLM system capacity. In effect, when growers choose their irrigation system capacity, they are choosing the level of risk that the machine will not be able to keep up with particularly high evaporative days. Growers who are not prepared to risk the possibility that their CPLM will 'not keep up' choose larger CPLM system capacities. The real consequences of choosing lower system capacities will be the reduction in the average amount of water held in the crop root zone as each passing day extracts on average more than the CPLM system capacity can supply. This does not necessarily mean crop failure, but rather the gradual decline in the readily available water supply for the crop and the potential for crop yield reduction.

For example, if the average 3-day peak crop evapotranspiration rate was 14.5 mm/day and the CPLM LEPA system capacity was 12 mm/day with continual operation, the average moisture content would decrease by 2.5 mm every day, and over 3 days this would create a total soil moisture deficit of 7.5 mm average across the entire field. This will not necessarily mean crop failure, but may lead to crop yield reduction.

A complete analysis of possible CPLMs system capacities and resulting irrigated crop performance in relation to regional peak crop potential evapotranspiration rates is only possible through the use of a crop model used for long-term climatic data in various growing regions with a wide range of system capacities.

Increased capital costs associated with larger CPLM system capacities do not necessarily increase in proportion to system capacity. For large lateral moves, whose upper size limit is currently controlled by the maximum flow rate of the largest pumps that manufacturers are prepared to place upon drive carts (typically a Cornell 10 RB @ 300 L/s), increasing the system capacity can be changed by decreasing the overall irrigated run length irrigated in any one season.

This is a cost-effective and simple matter as no substantial change to the lateral move design is necessary.

However, costs could be incurred if changes are necessary to the field drainage network.

Increasing centre pivot system capacities involves changes in the nozzle set, imposing a very minor cost. More importantly, however, alterations in the pump and pipe diameters, both in the span and supply line, can have significant associated costs. If pumps and pipes are incorrectly designed, the lifetime running costs of the system can be greatly increased.

Remember that choosing larger system capacities for CPLMs does not mean that larger water volumes are applied to the crop. Choosing greater system capacities for CPLMs simply means that there is adequate capacity to cater for the peak crop water requirements of well-grown cotton when the crop requires it most. As one cotton grower saying goes 'Change the things you can, and don't worry about the rest'.

Recent purchases of large lateral moves in the cotton industry have all been with the largest pump flow rate possible for these machines. There currently exists an upper pump size limitation to the flow rates possible through the larger lateral moves. This is based upon the largest flow capacity from the Cornell 10 RB, a highly efficient double volute pump preferred by the small number of companies building larger lateral moves. Based upon this fact, a range of different field lengths have been calculated and are presented in Table 5.5.4.

Table 5.5.4. Lateral move field lengths for various irrigating widths and system capacities with pump flow rates of 300 L/s, pump utilisation ratios 0.85 and 0.95 and an application efficiency ratio for LEPA of 0.98.

Irrigating width under lateral move in metres	Pump utilisation ratio – expressed as no. of days per 10 days	Wetted total field length for system capacity of 12 mm/day	Wetted total field length for system capacity of 14 mm/day
700	8.5	2570	2200
	9.5	2870	2460
750	8.5	2400	2050
	9.5	2680	2300
800	8.5	2250	1920
	9.5	2510	2150
850	8.5	2110	1810
	9.5	2360	2020
900	8.5	2000	1710
	9.5	2230	1910
950	8.5	1890	1620
	9.5	2110	1810

Running costs of CPLMs – implications of poor hydraulic design

One of the largest costs of ownership of CPLMs is the on-going pumping energy cost associated with supplying irrigation water through the machine. In the recent study of [CPLM operators in the QMDB](), 45% of growers were concerned with operating costs. Whilst energy costs are unavoidable when pumping irrigation water, about 70% of growers had an operating pressure that could be deemed to be excessive for the pressure regulators installed on their machines.

When designing CPLM systems, it is important to consider the potential energy costs of the system and minimise them wherever possible. This can be done by optimising the hydraulic design of the system, so that pressure losses are avoided and by ensuring the pump has been well matched to the system operating point and is not generating unnecessary pressure. Changing the operating point of an existing pump in an attempt to reduce pressure should be very carefully considered with appropriate professional advice as such alterations may impact pump efficiency and not result in the desired outcome.

From a design point of view, many growers who have purchased CPLMs in the past have not completely understood the implications of purchasing equipment with small pipe span diameters. Consequently, their overall cost of ownership was drastically increased when they purchased a slightly cheaper pipe span configuration. It is important to understand how increasing the overall upfront capital costs slightly can drastically reduce long-term ownership costs.

A present worth analysis of the long-term pumping energy costs of a large lateral move with four different configurations was conducted, as shown in Figure 5.5.18. This analysis translates the future costs of pumping energy involved with the lateral move into today's dollars. The analysis was carried out over a 15-year lifetime, with 587 ML being applied per annum through the lateral move. Pumping energy costs were \$1.43/ML/m head; an interest rate of 8% was used for this example. All spans available for this analysis were 48 metres long and two different diameter pipe spans were used as 6⅝″ and 8⅝″ nominal diameters. (Pipe diameter terminology is in keeping with current industry practice.)

The lowest cost option of the four different lateral move designs consists of 18 small diameter spans. The most expensive design consists of 14 spans of the larger diameter pipe spans. The economic and hydraulic modelling used to generate Figure 5.5.18 shows that increasing the number of spans with large pipes costs an additional 4%, but reduces the 15 year pumping energy costs to 80% of that from the lateral move with all small diameter pipe spans.

Similarly, when the analysis is conducted for a 9 span centre pivot, under the same economic modelling conditions and similar system capacity, the analysis shows that a 5% increase in capital costs can reduce the overall pumping energy costs to 60% of that of a centre pivot with all small diameter pipe spans (see Figure 5.5.19).

Figure 5.5.18. Cost of ownership for long-term energy costs and up-front capital for four different 18 span lateral move designs with numbers of larger diameter span pipes from 0, 6, 10 and 14

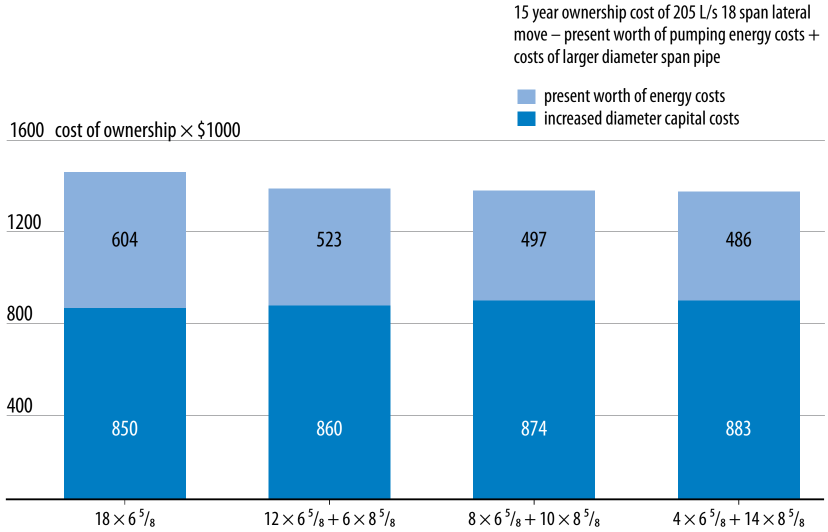
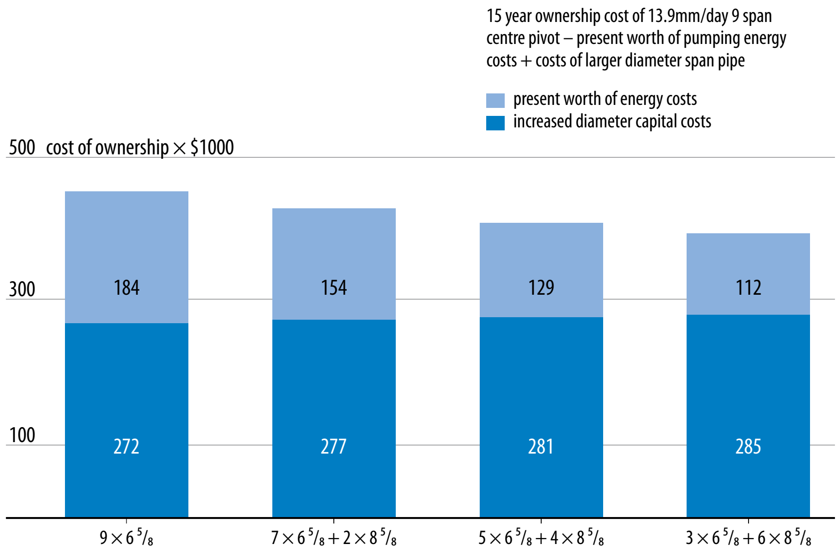


Figure 5.5.19. Ownership costs for long term energy costs and up-front capital for four different 9 span centre pivot designs with system capacity of 13.9 mm/day with the number of larger diameter span pipes increasing from 0, 2, 4 to 6.



Practical management tips for CP & LMs

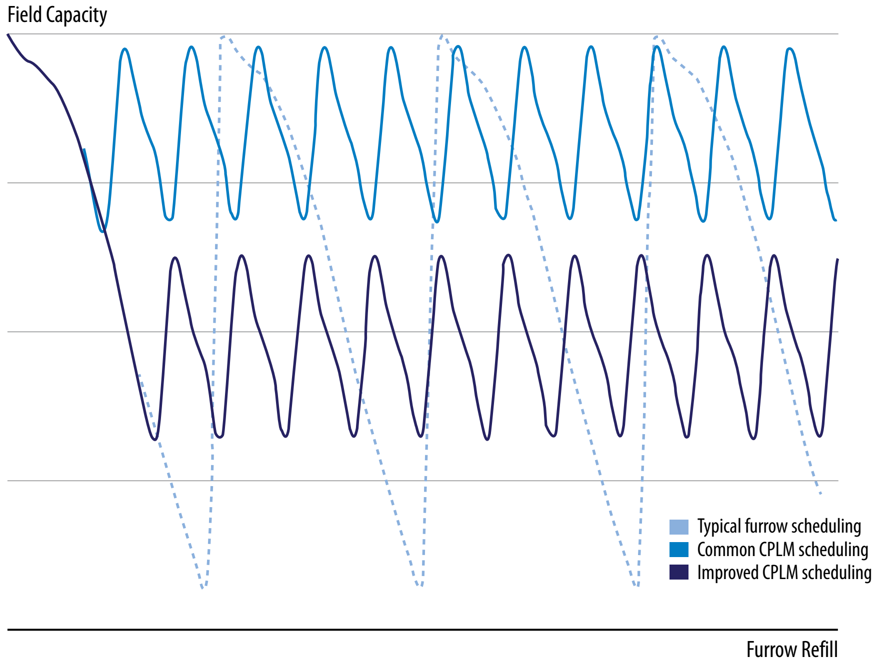
Crop growth and irrigation management

Management of crop growth under CPLMs can prove to be difficult for many who normally operate with furrow irrigated crops. For example, crops under these machines do not suffer from the waterlogging or large changes in soil moisture that can occur between furrow irrigations which often provide small amounts of crop stress and naturally prevent rank growth. Therefore crop and irrigation management under CPLMs is important to optimise crop growth and yield.

A significant advantage of CPLM systems is the flexibility to alter both the timing and the amount of water applied. This flexibility should be utilised by irrigation managers to give maximum benefit. Unfortunately, many growers are initially concerned about the ability of CPLM machines to apply enough water during periods of peak crop water requirement and therefore run the system with higher average soil moisture content than is necessary. This leads to an abundance of freely available water for the crop, possible rank growth and a reduced potential for rainfall capture.

A more effective strategy is to maintain the soil moisture below field capacity but above the normal furrow irrigation refill point to ensure the crop has access to ample water but to also allow maximum opportunity for rainfall capture (Figure 5.5.20). Regardless of the strategy used, crops are rarely saturated under CPLM irrigation and will be growing vigorously most of the time. Crop growth still needs to be monitored closely and the application of plant growth regulators, such as Mepiquat Chloride, may need a different approach to that used with furrow irrigation systems.

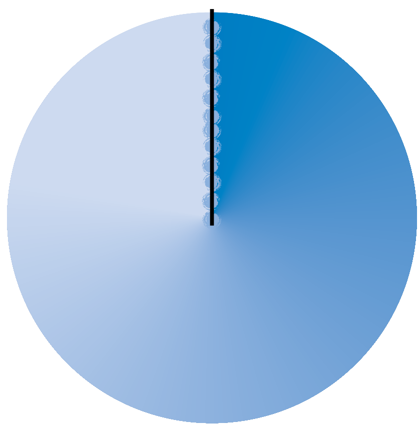
Figure 5.5.20 – Difference in soil moisture deficit under furrow irrigation and alternative CPLM irrigation scheduling strategies.



Irrigation management under CPLMs also requires operators to understand that the whole field does not have the same water status as is generally the case for furrow irrigation systems. It is more effective to view a field's water status as always gradational (except after rain) and that irrigation applications are also gradational due to the time taken for the CPLM system to traverse the field. Soil variations within a field add to this challenge.

As discussed in chapter 3.2, consider a centre pivot system that is applying 30 mm of water to a 50 mm soil moisture deficit. The soil immediately in front of the machine (about to be irrigated) would have a 50mm deficit whilst the soil immediately behind the machine (just irrigated) would have a 20 mm deficit (Figure 5.5.21). Assuming uniform daily water use, a point on the opposite side of the circle would be half way between these extremes, with a deficit of 35 mm. Such considerations can become complicated, particularly for new users and particularly after rainfall events. The OVERSched tool was developed to help visualise these soil moisture gradients so that irrigation management can be improved.

Figure 5.5.21 - Visualisation of potential soil moisture gradient in a centre pivot field. One side of the machine has dry soil whilst the other side has moist soil.



The use of soil moisture probes is also important, especially because CPLMs are often the size of several traditional furrow irrigated fields. This increases the likelihood of several soil types being present under a single system. When combined with rainfall events and the soil moisture gradients naturally expected across CPLM fields, this can make for challenging scheduling decisions.

At least one probe per major soil type should be installed and at least two per field is recommended. For centre pivots, the soil directly in front of the machine is the most different in moisture content (dry) compared to the soil immediately behind (wet). For lateral moves, this may be true in the majority of the run, but the opposite is the case at the end when the machine is about to commence the return pass – the soil immediately in front is the wettest.

Probes should be spaced evenly around the circle, or evenly between the beginning and end of a lateral field (preferably with a probe at both the beginning and end and one towards the middle). This means that the information that they give today will be used to make scheduling decisions for 2, 3 or 4 days into the future

Wheel track and wheel rut management

One of the most important issues any new grower faces in the first few years of owning and managing CPLMs relates to wheelruts and wheeltrack management. Few issues are more bothersome for a grower, but few are less discussed by dealers and manufacturers than the issue of wheel track and wheel rut management.

There are a number of things that growers can insist upon in the design of CPLMs that will lessen the anxiety many growers feel in relation to this troublesome issue:

- Boombacks upon wheel towers direct irrigated water to that part of the field behind the travelling machine, allowing the tower to run upon dry ground. Ensure that the boomback reaches a great enough distance behind the wheel tower to minimise the water thrown up on it.
- Use half-throw sprinklers on solid drops immediately around the towers to ensure water is not thrown directly into the ground, as is the case with soft hose droppers.
- Consider reducing nozzle sprinkler flow rates immediately adjacent to towers to 80% of their existing flow rates.
- Larger tyre and wheel sizes are more commonly installed on CPLMs today and many growers are successfully conducting trials where three and four wheels are driven inline upon the tower base, instead of the traditional two. Track and dreadnought options abound in the US.

A number of factors are important to remember when initially managing a new CPLM. As the first seasons pass, significant wheel track compaction levels rise and wheel rutting issues tend to decrease. This compaction is a significant help to the operation of your machine under saturated soil conditions and it is important to consider leaving it alone during deep ripping operations.

Germination

All growers using CPLMs should use sprinklers to germinate their crop, and it is essential that growers understand some of the ways that this can be successfully carried out.

The biggest difference when compared to furrow irrigation is the ability to plant the crop into dry soil and germinate with a number of light irrigation applications. Many growers are initially reluctant to plant on a bone dry soil profile for fear of being behind from the start (in terms of soil moisture) and not being able to "catch up". However if there is adequate system capacity, this should not be a problem. The soil moisture store can be gradually built up over the early part of the season whilst the crop demand is much lower than the system capacity which, as previously discussed, has been designed to cope with peak crop water use.

This approach is one of the largest advantages that CPLMs have over furrow irrigation in terms of water savings, as CPLM fields do not require inefficient pre-irrigation and also have spare soil moisture storage available to capture early season rainfall. A number of light slow irrigations throughout the germination period can also assist crops to move through soils prone to crusting.

Having suitable sprinklers is essential; the potential issues with high IAR static plate sprinklers and germination have been discussed previously. Growers using moving plate sprinklers may not need to have a separate setup for germination, but users of static plate sprinklers may find benefit from utilising a second nozzle set that reduces the total machine flow rate through the pump. This is sometimes called a dual nozzle pack and is one of the cheaper options that growers can employ to successfully apply water softly to freshly cultivated soils without inducing crusting and causing seedling emergence issues.

Note that this approach will require additional labour for manual switching of nozzles before and after germination. Users of LEPA emitters will also need to factor in a similar labour requirement as they switch from LEPA to sprinklers (possibly also with a reduced nozzle size) for germination.

Stubble retention is also likely to have advantages during germination as the retained stubble helps to hold the seedbed together, reduce crusting, protect seedlings and also improves infiltration both at germination and throughout the season.

LEPA irrigation systems

After germination and crop establishment, some growers employ LEPA systems to apply water throughout the rest of the crop life. When growers move to LEPA systems they need to remember that water is now being applied at much higher application rates than any soil is capable of retaining at the time of application. A critical part of the original LEPA system was to build a retention system into the soil before using the LEPA heads. This involves building small dams or dikes in the furrow between crop rows to capture the water applied at a very high rate. The original system developed in Texas was built for irrigation systems that are supplementary in nature and was only designed for machines with system capacities in the order of 5 to 7 mm/day. This means that while trying to use LEPA systems in Australia upon machines with system capacities of 14 mm/day, we are essentially using these systems at over twice their originally designed capacities. Growers need to ensure that while they are operating LEPA systems on CPLMs at these high system capacities that the soil being irrigated has the retention capacity in the form of significant cracking or soil surface roughness to hold water where it is placed. Alternatively, growers need to consider the correct implementation of dikes and small dams in alternate rows as part of the normal field preparation process for the use of LEPA irrigation systems.

Ensuring longevity from your CPLM investment

One of the simplest ways to ensure that CPLMs remain cost-effective is to ensure their longevity. Some of the greatest risks associated with the longevity of the valuable investment that you have made in the CPLM irrigation system come from the natural world. Provided below are a number of practical tips to ensure the longevity of your CPLM investment.

Corrosion – ensure that, if the water quality tests that your dealer has analysed prior to purchase suggest that the standard galvanised machine will be prone to corrosion, you invest in machines that are constructed of material that is resistant to corrosion. An additional 5% upfront investment in the capital cost of the machine can mean up to a five-fold increase in the life of the machine.

Ensure that, regardless of the water quality used in the machine, all water is drained from the lowest points of the spans: some span drain designs do not allow this, and other designs include automatic valves that have variable operational success. One alternative is to plumb this low span drain point out to a tee placed into the second or third sprinkler dropper. This overcomes both the tower and wheeltrack flooding at irrigation shutdown and ensures that there is no valve to become blocked by irrigation sediment.

The risk from overland flooding with CPLMs is minimal, except through flooded areas where fast moving water exists. Some growers install earthen berms (mounds of soil) raised above the flood-prone field level that allow growers to park the machine above the level of the floods. Gearboxes should be drained and refilled with new oil after inundation and electric control panels professionally cleaned and checked by professionals if they become immersed.

A number of CPLMs have been damaged by violent windstorms over the history of their use in Australia. A number of practical techniques can be employed by growers to prevent and or lessen the damage. Anecdotal evidence from machine constructors on-site during a violent wind storm report that the machine developed a bouncing action which threatened to loosen truss rods and collapse the recently built spans. The action of the wind past the round main pipe span was inducing vortices which alternately forced the main pipe up and down, causing the whole span to develop a wild bouncing action. Purchasing low-profile towers for low growing crops means that the span intercepts lower general wind speeds closer to the ground, in any wind event. Some growers park their centre pivots so that the centre point is directed into the prevailing storm path. Other growers operate their pumps and fill their machines with water to increase the weight and reduce the risk of these machines being moved by wind. Another option is to employ tie-down points at the end of field or on access roads. These can consist of submerged earth anchors such as large buried concrete blocks, vertically placed railway iron or wooden piles placed at intervals equal to span spacings, which have cable or chain attached to tie down span towers.

Modern tower gearboxes contain gas expansion chambers (flexible rubber diaphragm enclosed within steel enclosures) that allow for the expansion and contraction of the gases and liquids in the gearbox during heating and cooling, without creating differential pressure upon the axle seals. This design does not allow suction pressure to build up on the axle seals of the gearbox when it is cooled during sprinkler irrigation, thus preventing water being drawn into the gearbox to corrode drive trains. In any instance, ensure that sump plugs are regularly removed and water is drained from gearboxes. CPLM manufacturers specify gearbox oils that have properties allowing water to separate from oil and settle to the bottom of the gearbox.

Towable gearboxes are available in a number of different designs, with the older style having caused enormous difficulty for growers over the years. The original design contains a second set of bearings that are positioned outside the original axle of the gearbox. They are configured so on removing a single pin, the wheel hub disengages from the gearbox axle. This allows free rotation of the wheel during towing of the centre pivot from one site to another upon this secondary bearing system. Over time the pin and secondary bearings wear and allow movement of the wheel hub upon the gearbox axle, resulting in a failure of the gearbox drive train. More modern designs allow the worm gear to be physically disengaged from the bull gear in the gearbox, so that the wheel hub remains attached to the original gearbox drive axle. They do not use a secondary set of bearings within the drive-line.

Ensure that you flush the main span pipes on a regular basis, especially if you are using any surface water or groundwater bores that are pumping sand. This will ensure that excessive sediment weight is removed from the spans, particularly overhangs, where this material tends can accumulate and induce additional loading stresses. Corrosion that can occur underneath these saturated sediments upon the wall of galvanised pipes can lead to early pipe failure. Many growers install large valves upon the end of the overhang and last spans to allow higher water velocities to scour sediment from the pipe spans when the valve is opened.

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5.6 Drip irrigation: design, installation and management

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Key points

- A system designed by a row crop engineer who is experienced, preferably in cotton, is critical to achieve the potential water savings and flexibility in crop management that drip irrigation can offer.
- A well-planned maintenance program is essential to maintain proper system operation.
- It is important to monitor and control the quality of water used with the drip system, which determines the frequency of flushing required.
- Drip allows accurate application of water and fertiliser to suit crops' requirements and flexibility in field operations, but the management requirement is higher than conventional surface systems.

Drip irrigation has the ability to optimise water and fertiliser use in row crops. When crops are irrigated daily with small volumes, the potential yields can be increased and maintained, or crops can be finished faster in short season areas.

Drip irrigation is a relatively new technology. It has been used in row crops for just 20 to 30 years. In Australia, drip has become the standard irrigation method in high value permanent crops. Worldwide it is becoming more widely used in row crops.

The widespread adoption of this technology has been largely restricted by high costs involved in setting up a system. With the increasing pressures on growers to increase water use efficiency and maximise production, drip will definitely play a role in many developments.

Drip irrigation is a system of pressurised water run through tubes placed in the field. Emitting devices are placed at intervals along the tube, so water is distributed uniformly. In most row crop situations today this tube is buried, and known as **subsurface drip irrigation** (SDI).

With SDI, water is placed into the plants' root zone, and therefore losses due to evaporation and run-off are minimal. The uptake of the applied water can be very efficient with accurate management, as water is applied daily with fertiliser added as required.

The system capacity is measured in millimetres per day. Systems are most often designed to replace the peak potential daily use of the crop, around 12 millimetres per day. Systems should not be designed for a lower supply rate because the risk of under-supply is increased if rain doesn't arrive as expected. Each day the grower can alter the applied water to keep soil moisture levels in optimum range. Soil moisture levels can also be manipulated to influence crop growth habit.

The practice of fertigation, or irrigation with fertiliser added, is as important as water is with drip irrigation. Soluble fertilisers are taken up faster and more effectively, and fertiliser can be added daily, reducing leaching and soil losses. Drip has the ability to apply very small quantities of elements, uniformly and precisely as required with irrigation water.

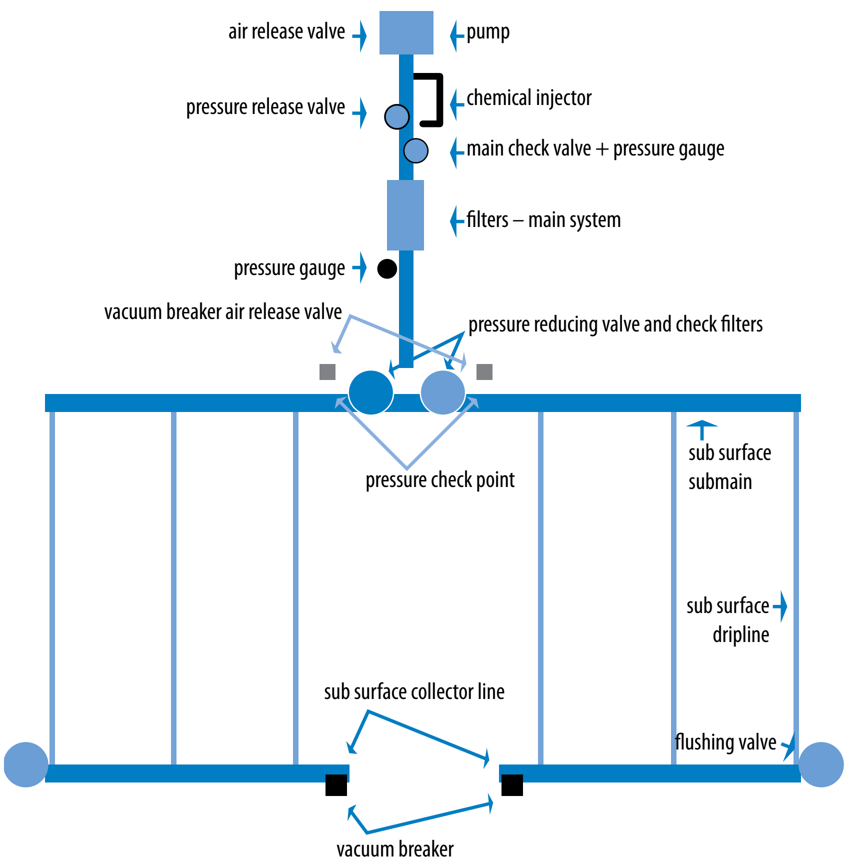
For further information, refer to WATERpak chapter 5.8.

Design of drip systems

A drip system contains some standard components (Figure 5.6.1), but each system is tailormade to the fields' requirements. Soil, water and farming systems all play a part in the system's specifications. As a result it is difficult to compare outcomes.

It is important that a prospective user of drip irrigation assess their aims and goals prior to a system being designed.

Figure 5.6.1. A typical drip irrigation system design



SDI systems require the following components:

Pump – carefully selected for performance and safety, an SDI pump's performance curves will often be 'flat' with maximum pressures below that of the pipelines.

Filtration – variety of filtration methods, sand media or disc filtration being the most common. Nearly all are automatic flushing. Micron or 'fineness' of the filters is determined by the drip tube manufacturer – they do not all have the same requirements! (Figure 5.6.2).

Pressure gauge – to check pump output pressure and pressure after filters; difference between the two is how blocked filters are.

Fertiliser injector – pumps or venturis for fertiliser injection and maintenance.

Water meter – for performance checks and safety.

Controller – an electronic computer runs field valves and system safety; also turns pump off and sometimes on.

Mainlines – Mostly PVC, designed for cost-effective movement of water to fields.

Air valves – very important that these are installed and working. Trapped air can compress, releasing at pressures much higher than pipes are designed for. Air valves are located at all valves and high points in mainline, and must release air whilst under pressure; they are often dual purpose air/vacuum release.

Valves – mostly hydraulic regulating valves, these reduce pressure from mainline to suitable operating pressure for drip lines. Require pressure check points either side for setting valves and checking performance.

Vacuum release valves – these are important to let air back in after system shut down, are located downstream of valves and at all ends of submains and flush collection manifolds, and prevent air including mud being sucked back into emitters.

Submains – critical to system uniformity, drip tube is connected to these; they are positioned after valves, so pressure differences relate to dripper flow rates.

Drip tube – the real key to system operation. Various flow rates, spacing of emitters and diameter of tube. These attributes all play a part in run lengths and costs and uniformity, and can be confusing. Should be determined by soil types and uniformity and flushing ability. Wall thickness is also an issue; a thicker wall is more resilient to damage.

Emitters – not all emitters are the same: they vary in clogging resistance, CV (coefficient of variation, that is, emitter uniformity), size of flow path, ability to clean inlet filter, length of labyrinth (shorter path means more efficient, more turbulent and easier to clean). Beware of low flow rate emitters in long-term systems.

Flushing manifold – the collection pipe where drip tubes are connected, these are opened for flushing out dirt. They are not necessary but greatly reduce maintenance times. Also, they have more vacuum release points.

Figure 5.6.2. Filtration equipment

An experienced, qualified irrigation designer should design all drip systems. For cotton systems they should be experienced in row crop designs and have a record of successful projects. The designer should consult with growers and consultants to ensure the project has the highest chance of success, fitting with farm infrastructure and long-term farm plans. To do this the designers must have adequate information to work with. This will include: accurate GPS maps and contour maps showing 0.5 m variations in slope, field layout and size, access and roads, soil properties and possible changes in soil types. If field conditions are variable, this detail will enable the designer to develop a system that will allow separate within-field management. A detailed soil survey may also be useful.

Almost all SDI row crop systems use non-compensated emitters, meaning the output changes with pressure. Uniformity is a major issue in design and can be complex. Systems can be designed much more cheaply if uniformity is compromised. This makes management very difficult always having to manage for the 'middle or dry' areas. Uniformity is measured in a few ways, the most accurate being **field flow variation (FV)**. This is represented as a percentage, for example, FV ±7% means all emitters in the block or valve will perform better than 7% either side of the specified flow rate of the design. Few row crop designs are adequate beyond ±7% FV. It is important to compare similar uniformity measurements, as it is easy to confuse them.

Installation of drip systems

Good installation can improve performance and longevity. Extreme care and high levels of supervision are required to ensure systems are installed correctly and best suit the farm and the grower. Often problems can be avoided if small changes are made to placement of flush points and other equipment. There should be almost no aboveground components within fields, locating flushers and valves beyond fields, or they can at least be grouped and protected.

Accurate injection of tube is also critical and specialised equipment is available for placement (Figure 5.6.3). Emitters should always be positioned facing upward and into loose soil. Bed preparation and pre-ripping can make accurate depth and location much easier (Figures 5.6.4 and 5.6.5). The use of global positioning satellites (GPS) is now considered essential, making relocation of beds possible over time.

Figure 5.6.3. Tube installation equipment

Figure 5.6.4. Depth of tube placement is critical

Figure 5.6.5. Placement within bed system prior to sowing

Drip tube connections should be perfect. Risers from pipelines should be accurately drilled. Extreme care is needed filling trenches. The system should be pressurised and loose fill delicately pushed into trenches to prevent movement and kinking of risers or tube.

Accurate depth and straight trenches with smooth, soft floors will allow good support of pipes (Figure 5.6.6). PVC pipe, elbows, reducers and ends should be adequately thrusted to prevent movement, following the pipe manufacturer's instructions. Valves and command tubing should be supported if required, and protected from machinery and animal damage. Control systems need to be electrically protected from both supply and lightning.

Figure 5.6.6. Trench construction

Photograph all major valve assemblies and pipe junctions before backfilling. This is a big help if they ever need repair.

Maintenance of drip systems

Like any complex system or machine, drip systems need maintenance to prevent breakdowns and loss of performance.

Maintenance requirements need to be included in the design. Drip tube sizes and run lengths are often determined by flushing capability. Keeping systems clean, particularly on silty river water, is the key to emitters' longevity. The tube and emitters don't degrade or break down. If kept clean, very long life can be expected – often, with the high cost of establishment, 10 years or more. There are systems that have been well maintained that are beyond this age and performing as new.

Maintenance is largely preventative, with silt and organic matter needing to be removed with water. Inlet water pressure to tubes may need to be raised to achieve scouring velocity in the tube once ends are opened. This will be indicated on the design. Frequency of flushing is determined by water quality. Monitoring system flow rates on the water meter can reveal emitter clogging.

Flushing needs to be commenced from the pump onwards. Ensure filters are cleaned well and pressures set. Progress systematically, cleaning mainline, submains, then drip lines.

In most situations additives such as chlorine and acid may need to be used. Chlorine kills algae and can loosen up bonded organic matter, enabling it to be flushed out afterwards. It is important to understand there is no particular volume of chlorine that will achieve this task. Silt and organic matter consume chlorine as it proceeds through the system. An injection rate of chlorine can be calculated and must be injected until free or spare chlorine is sampled at the farthest point. Rates of between 5 to 20 ppm chlorine may be required, depending on the severity of the problem. Irrigation suppliers and some manufacturers can supply the necessary technical help to keep this job as cost-effective as possible.

Acid injection is often over-recommended. In other parts of the world, acid is very cheap and can be used in place of chlorine, although high rates are needed. It should really only be used for chemical-based deposits, and works on the basis that solubilities of chemicals change with pH. By dropping the pH of water, these chemicals may become soluble again and can be flushed out.

To accurately calculate the volume of acid required to drop the pH of the irrigation water, simply perform a bucket titration. Get 10 litres of irrigation water; add acid one millilitre at a time and test pH until water drops to desired pH. Using these measurement and system flow rates, an injection rate in litres per hour of acid can be calculated.

ADD WATER TO ACID!

The exception in the use of acid is for root intrusion, where the corrosiveness of the acid is used to break down intruding root material. Very high rates are required and it is very expensive. Prevention is by far the best method.

Strategic use of herbicides is effective in preventing the roots' entry to emitters. When injected late in the irrigation, herbicide stays close to the emitter outlet, making this an unattractive area for the roots to enter. Careful cutting back of water can also reduce the tendency for roots to search for more water.

Before and after addition of acid or chlorine the drip systems should be flushed strongly with water. This reduces consumption of chlorine and buffering of pH by silt and organic matter that are easily removed. Flushing after treatment is important to prevent loosened material attempting to exit through emitters and clogging them.

Pumps, filters, valves and control systems also need maintenance. This can most often be carried out in the off-season. Suppliers and some manufacturers can provide advice or a service to do this work.

In summary

Drip irrigation is one of the most powerful agronomic tools available to the grower. It allows accurate application of water and fertiliser to suit crops' requirements and push plants to achieve their potential. Field access is increased with no flooded period. Labour costs can be reduced, with large areas being centrally controlled. Grower lifestyle can be improved with planned tasks and little odd hours or heavy work. Complex fertiliser regimes or watering strategies can be implemented easily. Drip systems can be designed to suit irregular fields and difficult soil types. Many current systems are purchased for this reason alone.

As demand increases for higher crop production with efficient use of resources, drip irrigation will provide the ability to accurately manage crops to achieve the forward-thinking grower's goals.

The best way to determine if drip irrigation is suitable for your situation is to talk to other growers who are using this system. Your local extension officer should be able to connect you to such growers. Some examples of growers who have used drip irrigation for cotton are available online and in the case studies that follow.

Case study 1 - evaluating drip irrigation: Lower Namoi Valley

Steffan Henggeler
Integra Management Systems

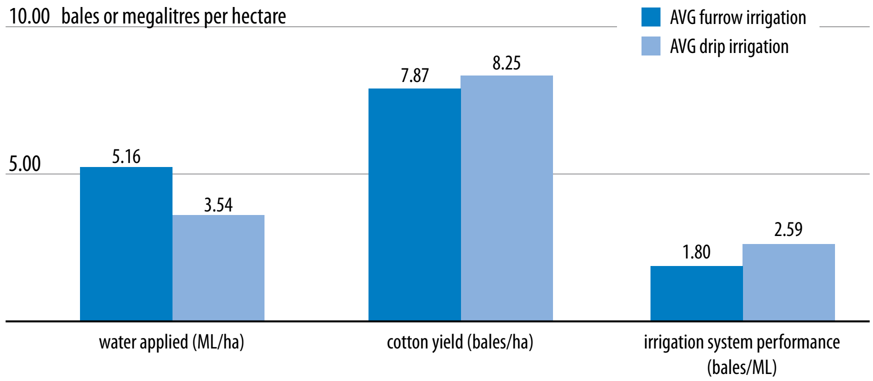
Irrigation system performance

The drip system installed at Auscott Narrabri worked very well with only minor technical problems. One of the issues we faced was that the lines and at the head ditch end of the field were not buried deep enough and therefore dug up a couple of times while scarifying the rotobuck area. Diligence when installing drip systems is crucial.

The system performed well and even issues such as watering up after planting were not a problem in our soils.

The yield results over the four trial years were quite consistent, with small variability only. The fourth trial year (1999-2000) is not included in Figure 5.6.7 but has performed very similar to the average of the first three years: because it was a cool season, water savings were not quite as high, but still around 20%. Yield difference was 0.395 bales/ha before ginning in favour of drip, and therefore pretty much the same as the 3-year average.

Figure 5.6.7. Increased irrigation performance of drip irrigation compared to furrow irrigation



(Note: No measurement of deep drainage or evapotranspiration)

It should be noted that both yields and furrow irrigation performance have increased dramatically across the industry since 2000 and will most likely continue to do so in the future. Therefore, it is imperative that growers considering investment in alternative systems investigate the recent performance of these systems by talking to other users and searching for up to date research and trial results.

While the system itself performed technically very well, the necessary yield differences to pay for the additional capital investment for drip irrigation were not achieved under the soil and climatic conditions of our trial.

For this reason, the drip system was moved from Auscott Narrabri to Auscott Warren, where it is very successful on a red soil. The yield difference achieved in the first year on red soil of 1.73 bales per hectare made drip irrigation a valuable investment at this site.

Additional benefits

Substantial water savings (20% to 30% of applied water) were achieved using drip versus furrow irrigation, even on heavy clay soils. Those savings are likely to be even higher on lighter soils.

However as furrow irrigation performance across the industry has increased, the water savings offerred by alternative systems may not be as large as they once were. Recent research into CPLM systems has indicated the magnitude of water savings has decreased (see WATERpak Chapter 5.5) and the same may be true of drip irrigation systems.

Drip irrigation allows the usage of ground rigs all season (except after rain) and therefore reduces the risk of off-target chemical drift as well as decreasing insecticide cost early in the season (banded sprays).

Drip reduces the need for physical labour and therefore potentially reduces the chances of workers compensation costs. It also suits an older workforce (experienced irrigation operators with reduced physical abilities).

Drip reduces soil erosion and therefore decreases de-silting costs. It is also better suited to zero-till farming systems than furrow irrigation because it avoids waterlogging.

Financial considerations

Drip systems should probably be installed on land not previously developed for irrigation, because when considering the capital put into development, you do not work with the full development cost, but only the difference between the cheapest option (for example, furrow irrigation) and drip irrigation.

The capitalisation of water savings (in our case, around 1.5 ML/ha @ $1200/ML) needs to be taken into account to be able to justify drip irrigation versus other irrigation systems.

To capitalise on the great expense, soils should be chosen for new systems that favour drip irrigation and are less suitable or even unsuitable for furrow or lateral move. This will increase the yield benefit and therefore the return on capital, hence the recommendation to move our drip project to Warren.

Choose a field protected from flood and other external influences to protect invested capital.

Centre-fed systems are less expensive than side-fed systems, mainly due to decrease in cost of laterals.

Issues when considering drip irrigation in cotton

Some design specifics for the Auscott trial site:

- 1 lateral tape around 25 cm deep every 2 metres, in the middle of the wide bed
- 1 dripper/50 cm @ 1.1 L/h

Design of filtration to take muddy water out of a channel

The maximum row length for 35 mm tape seemed at the time to be 700 metres. No valves, fittings or joiners are in the field. The problem is not system uniformity while the system is applying water, but to achieve water flows fast enough when flushing the system when longer than 700 m. Using long run length therefore demands less frequent irrigations to minimise the filling and emptying times of the lines as the main source of bad uniformity in 35 mm tapes.

To my knowledge, it is still doubtful to date (2002) if 700 metre drip tapes are successful.

Centre-fed systems require a tail drain in the middle of the field to allow access to submains and fittings during the season and still drain off stormwater. Practically, it means that fields are split in half to a maximum length of 400 to 450 metres.

Do not under-design a system in regards to its capacity to save on initial capital costs! The system needs to be designed to be able to grow the highest yields possible to make it worthwhile. The Auscott trial system was designed to supply 13 mm per day.

EnviroSCAN® tubes proved themselves very well suited for scheduling water applications. Soil moisture can be monitored on a regular basis to avoid deep drainage. In our heavy clay soils, 6 hours application per irrigation and section was ideal to keep the water in the root zone. On lighter soils the optimal application time is likely to be shorter.

The installation of a good fertigation injection system is very important. Evidence from other drip systems suggests that spoon-feeding of nutrients through drip could give additional yield benefits we have not yet explored in our trial. We installed a very simple and cheap but effective system using a mixing drum, separate water supply through a float valve and a fire fighter to inject fertilisers.

Absolutely crucial are a well-designed maintenance system and a maintenance procedure to avoid silt and algae build-up as well as root intrusion.

The quality of the installation will make or break a system. Purchasing a fully installed system should be considered instead of doing some of the critical jobs yourself. This approach clarifies the responsibilities when potential system faults occur.

All parts and fittings have to be checked by the owner of the system for leaks, kinks and so on before trenches are filled in. Avoid being caught by rain while the trenches are still open. The order of installation of the different system components is also very important: **laterals last.** Laterals have to be filled with water as soon as possible after installation to reduce the risk of insect damage.

Suppliers and installers offer after-sale service to get the system working to its full potential (irrigation scheduling, fertigation and maintenance).

Case study 2 - evaluating drip irrigation systems: Yambocully

Peter Cross
Corish Farms, Goondiwindi

We decided to give subsurface drip a try after hearing about the water savings to be made and looking at some of the systems in the Macquarie Valley.

The area we were looking at to develop was a ridge in the middle of the farm. This area was impractical to develop for furrow irrigation because of the amount of soil to be moved and the number of point rows we would create.

Our reasons to go ahead with subsurface drip were:

- water savings to be had
- use of land inside developed area
- keen to give it a go
- potential for higher yields.

Summary of our experience

Negatives of drip:

- high capital costs of installation
- potential problems of wet harvest
- some soil types are hard to wet up
- life expectancy of tape is unknown
- thin walled tape is prone to insect damage

Positives of drip:

- lower water use – 35% to 40% less than furrow irrigation
- higher yields
- less crop stress due to waterlogging
- able to use rainfall more effectively
- fewer OH&S issues – for example, less manual handling, less chemical contact when watering while spraying
- lower labour costs
- better soil tilth (in our case)
- fewer workings
- fertigation – feed as you need
- greater ability to use stored water at the end of the crop
- use ground unsuitable for furrow irrigation

Must haves:

- natural drainage
- system that can deliver peak daily water use of crop
- good distribution uniformity
- good filtration
- soil moisture monitoring tools
- maintenance program
- correct installation (use a guidance system)
- position valves to suit soil types and slopes

The system has worked well for us, especially the second installation with heavier tape. We have achieved a water saving over the last 4 years of 35% to 40%.

This has enabled us to grow 2 bales of cotton for every megalitre of water applied consistently.

Drip versus furrow irrigation: 1999–2000 and 2000–01 seasons

Introduction

The two seasons were very different, with 1999–2000 having almost perfect growing conditions, which produced some very high yields, while 2000–2001 was almost the opposite with some very low to moderate yields. This was caused by some adverse climatic conditions – an extremely wet November, followed by a very hot January and another very wet period in January/February. However, there were still some significant differences between drip and furrow irrigation fields.

Outcomes

The main difference between furrow and drip irrigation was still the water saving (Table 5.6.1) plus a small increase in yield under drip irrigation (Table 5.6.2). Table5.6.3 notes the increase in bales produced per megalitre with drip.

Table 5.6.1. Water savings made under drip irrigation

Megalitres of water applied ML/ha		
Season	Furrow	Drip
1999-2000	7.0	4.2
2000-2001	7.2	5.0
Average	7.1	4.6

The increase in water usage under drip in 2000-01 was caused by the very dry winter, with drip using 1.6 ML/ha to wet up at planting time.

Table 5.6.2. Yields for both seasons under furrow versus drip irrigation

Average yields Bales/ha		
Season	Furrow	Drip
1999-2000	9.02	10.34
2000-2001	7.7	8.1
Average	8.36	9.22

Table 5.6.3. Bales per megalitre produced for both seasons: furrow versus drip irrigation

Bales/ML		
Season	Furrow	Drip
1999-2000	1.28	2.46
2000-2001	1.08	1.6
Average	1.18	2.03

Case study 3 - Oxygation: using aerated irrigation water for drip irrigation

Lance Pendergast
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Oxygation is a term used to describe the use of aerated water (at the rate of 12 per cent air by volume of water), for subsurface drip irrigation. Positive effects of oxygation were noted consistently on lint yield over a number of seasons without the need for additional water application.

A long-term oxygation field study from 2004 to 2012 on a vertisol soil at "Nyang" Emerald measured the effects of oxygation on cotton lint yield, quality and water use efficiency (WUE), as well as long-term changes in soil chemical, physical and biological properties.

The trial aimed to determine the longer-term effect of oxygation and evaluate aeration uniformity and crop performance along the lateral row length.

In the first two seasons the effect of oxygation was quantified at two irrigation rates (85 per cent and 105 per cent of crop evapotranspiration (ET_c). In 2006/07 there was insufficient water for the trial due to drought. In the 2007/08 and 2008/09 seasons only one irrigation rate (85 per cent ET_c) was tested. In subsequent seasons, the irrigation rate was increased to 100 per cent.

Positive effects of oxygation were noted consistently on lint yield over a number of seasons. Yield increased with oxygation in all trial years when irrigation rate was maintained at 85 per cent of ET_c or above. An increase in WUE was associated with higher yield in the oxygation plots for the same amount of irrigation water applied. Yields in all years benefitted from oxygation, although the difference was not statistically significant in every year. The average yield increase across all years was 14.7 per cent (Table 5.6.4).

Table 5.6.4. Lint yield (bales/ha) was generally higher in oxygation plots

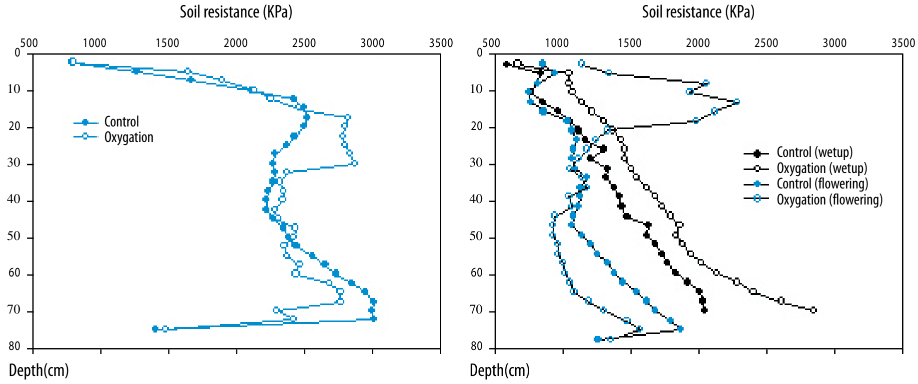
Treatment	2004/05	2005/06	2007/08	2008/09	2009/10	2010/11	2011/12	Combined
Oxygation	9.32	9.33	8.84	6.90	9.11	9.04	11.21	9.10
Control	7.35	8.02	7.89	6.47	8.33	7.71	10.62	8.05

A number of controlled environment studies suggested that the aeration can be non-uniform along the drip lateral. Intensive plant sampling and data collection along the length of drip line was conducted in a number of seasons.

Field data from the trial in 2005/06 suggest that there is no major difference in terms of benefit of oxygation along a drip line until beyond 165 metres from the start of the drip line.

Likewise in 2008/09 and 2011/12 there was no differential effect of oxygation according to distance from the air injection point, although in both the latter years there was an indication of a positive effect further from the injection point.

Figure 5.6.8. Soil compaction was often higher in the oxygation plots.
Left – at the end of the 2008 - 09 season.
Right – during wet up and flowering stages in 2010-11.



We did find effects of oxygation on soil penetrometer resistance, which increased with oxygation due most likely to the more effective water uptake and drying of soil with oxygation (Figure 5.6.8). Soil biological activities (as indicated by increased fluorescein) were enhanced (Table 5.6.5) in the oxygation treatment compared to the control.

Table 5.6.5. Effect of long term oxygation on soil biological properties, Nyang, Emerald

Treatments	Fluorescein (µg /g dwsoil/h)	CFU bacteria (Log)	CFU fungus (Log)	Soil respiration (g com m-2h-1)
Oxygation	46.49±0.87	5.81±0.061	3.50±0.106	0.890 ± 0.079
Control	42.68±0.79	5.93±0.055	3.51±0.051	0.698 ± 0.041
Furrow	36.32±1.38	5.96±0.062	3.22±0.100	

NB: Amount of fluorescein produced by the hydrolysis of fluorescein diacetate (FDA) is directly proportional to the microbial activity in the soil (Swisher and Carroll, 1980)

A simple economic analysis (Tables 5.6.6 and 5.6.7), indicates a return on investment of $562.50 per hectare per year, giving a payback period of a little over two years.

Table 5.6.6. Details of cost to retro-fit air injection to 0.4 ha plots at current site

Item	Unit	Price ($)	Cost ($)*
Venturi injector	1	265	265
PVC elbows	4	10	40
PVC t-pieces	2	10	20
Valves	2	45	90
Pressure gauges	2	30	60
TOTAL			**475**
Cost of oxygation 1 ha (475 x 2.5)			1187

* Costs would be less if installed with new system

Table 5.6.7. Details of returns per ha at current site

Yield (control)	Yield (Oxygation)	Yield difference (bale/ha)	Cotton price ($/bale)	Return on investment ($/ha/year)
8.05	9.10	1.05	500	525
Return to investment, yrs (1187/525)				2.26yrs

Further Information

Irrigation Australia

NSW DPI

Pendergast, L. (2012). Benefits of aeration of subsurface drip irrigation water – field evidence on CQ highlands vertosols. PhD thesis, CQUniversity, Rockhampton, Australia, pp245.

Midmore, D. J. Bhattarai, S. P. (2012). Oxygation- Optimising delivery and benefits of aerated irrigation water. NPSI Final report.

5.7 Fertigation

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Ian Rochester
CSIRO, Narrabri

Key points

- Fertigation can provide flexible and precise application of crop nutrients, but requires an efficient irrigation system and good management.
- In pressurised systems, venturi injection and positive displacement pumps are alternative fertigation methods.
- In surface irrigation systems, fertigation is typically limited to 'water-run urea'. Irrigation performance and the volume of tailwater created are critical considerations for efficient fertigation. If irrigation is non-uniform, the water flow rate changes, or the rate of urea addition changes, then the uniformity of fertiliser application will be affected.
- Not all fertilisers are suitable for fertigation as some are insoluble. Furthermore, the compatibility of different fertiliser products should be checked before applying simultaneously.
- It takes some time for fertiliser to move through the irrigation system, which should be taken into consideration when determining fertigation run times and flushing duration.

Fertigation is the practice of applying fertiliser in a liquid form to a crop via the irrigation system. Using the irrigation system to apply fertiliser reduces the need to use mechanical operations and sometimes eliminates them altogether. More and more we are seeing greater percentages of annual crop fertiliser requirements being applied via fertigation, to the point where some cropping systems receive 90-100% by this method. When combined with an efficient irrigation system, both nutrients and water can be manipulated and managed to obtain the maximum possible yield of marketable production from a given quantity of these inputs.

Fertigation is typically used to address fertiliser deficiency which inhibits plant growth, labour and operational efficiencies. Fertigation has many advantages and disadvantages. The advantages include:

- fertiliser can be applied directly to the root zone optimising plant growth
- nutrients can be applied any time during the growing season based on crop need
- highly mobile nutrients such as nitrogen can be carefully managed to ensure rapid crop uptake
- fertiliser can be applied quickly to address any deficiency issues
- minimal crop damage
- tractor operations are reduced, saving fuel, wear and labour
- well-designed injection systems are simple to use and suit automation
- little amounts of fertiliser applied often leads to reduced off site impacts
- reduced loss of fertiliser due to unseasonal weather

Disadvantages of fertigation include:

- heavily reliant on the efficiency of the irrigation systems distribution uniformity
- heavily reliant of overall irrigation infrastructure design / layout depending on injection point
- potential issues during wet weather

Fertigation is used in overhead (centre pivot and lateral move), drip and surface irrigation systems.

Fertigation in Pressurised Systems

The two main injection systems used in overhead and drip irrigation systems are Venturi injectors and positive displacement (pressure) pumps.

Venturi injection

Venturi injectors come in several sizes and can be operated under different pressure conditions. Venturi injectors are only usable on closed pipe systems as they are set up in a shunt pipeline parallel to the main irrigation pipeline close to the pivot or lateral structure.

Requiring at least a 20% differential pressure to work properly, irrigation water from the main pump is passed through the venturi unit, creating a pressure differential between the water bypassing the unit and the fertiliser solution in the tank. This pressure differential causes the solution to be drawn up into the mainline. The gate valves and flow rate control the rate of the fertiliser solution applied. The venturi draws all the fertiliser until the tank is empty. Venturi injectors do not require external power to operate but some units utilise a small booster pump in the shunt pipeline to produce a differential pressure. Injection rates of 10 to 20,000 litres per hour can be achieved.

Figure 5.7.1 demonstrates how the concentration level remains reasonably constant over time or throughout the fertigation cycle with fluctuations only due to variable pressure differential. This constant is only achievable when a large fertigation tank is in place and all fertiliser is in solution as no extra water is added during the process.

Figure 5.7.1. Injected concentration over time using a venturi system

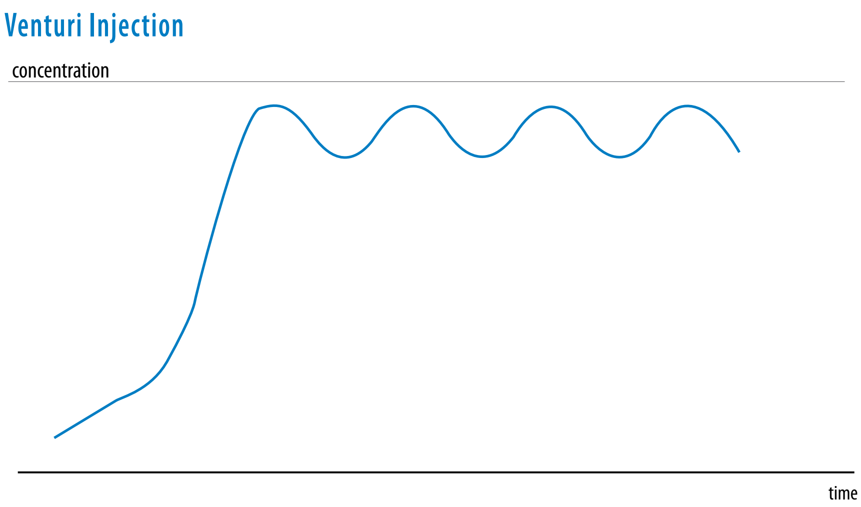
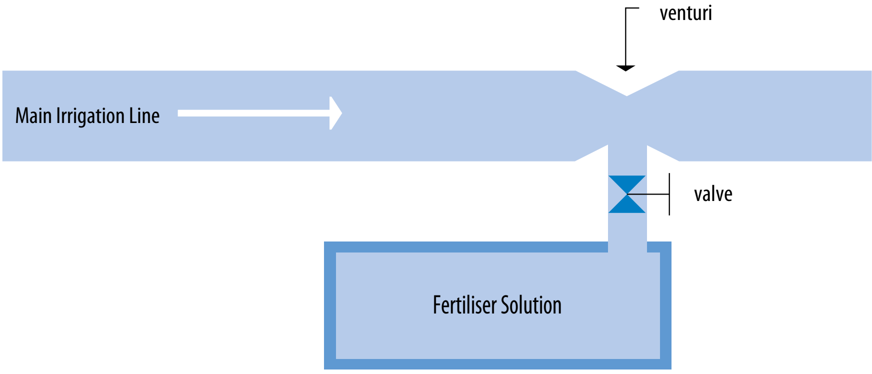


Figure 5.7.2: Schematic of a venturi system



The advantages include:

- no moving parts – typically manufactured from plastic
- requires little maintenance
- gate valves control fertiliser injection rates with some accuracy
- large volumes can be mixed and stored on site
- reduces OH&S issues in dealing with fertiliser

Disadvantages include:

- requires a closed pipe system
- requires pressure loss in main irrigation line (can be up to 33 per cent)
- automation is difficult but not impossible

Positive displacement

This is the most common method of injection of fertiliser into irrigation systems and is very accurate. The three systems available are electric injection pumps, piston-activated pumps and diaphragm activated pumps. Piston-activated and diaphragm-activated pumps are both hydraulic injection pumps. Electric injection pumps include single or multiple piston, diaphragm, gear and roller pumps. These can be regulated to achieve the desired rate by:

- adjusting the length of the stroke of piston pumps
- metering flow
- manipulating pump speed at the pulley
- using a variable-speed motor
- semi-automation via electronic pulse water meters

Advantages include:

- simple and effective
- relatively easy to install
- no pressure loss in the main irrigation line
- automation is relatively easy

Disadvantages include:

- pumps must develop a minimum mainline pressure to operate
- potentially need electric power source to operate
- require a certain level of maintenance
- selected pump must be stainless steel and/or have a bronze impellor

Figure 5.7.3 demonstrates how the concentration level remains constant over time or throughout the fertigation cycle. This constant is only achievable when a large fertigation tank is in place and all fertiliser is in solution as no extra water is added during the process.

Figure 5.7.3. Injected concentration over time using a Positive Displacement (Direct Injection) system

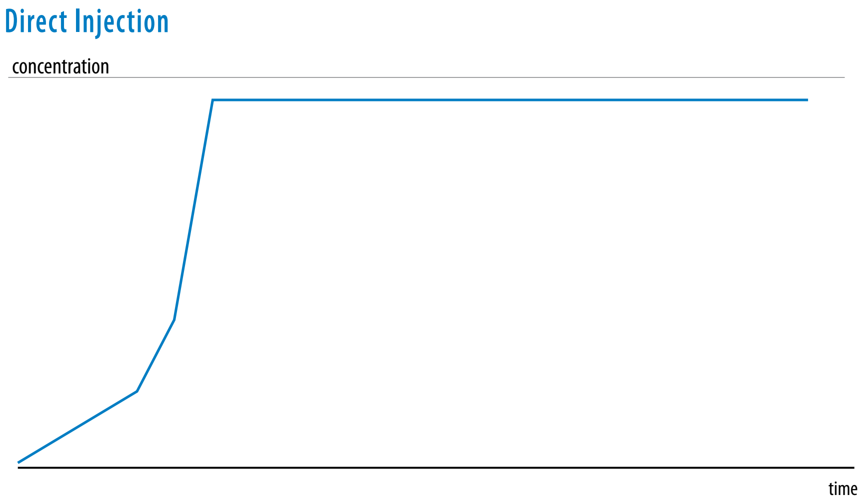
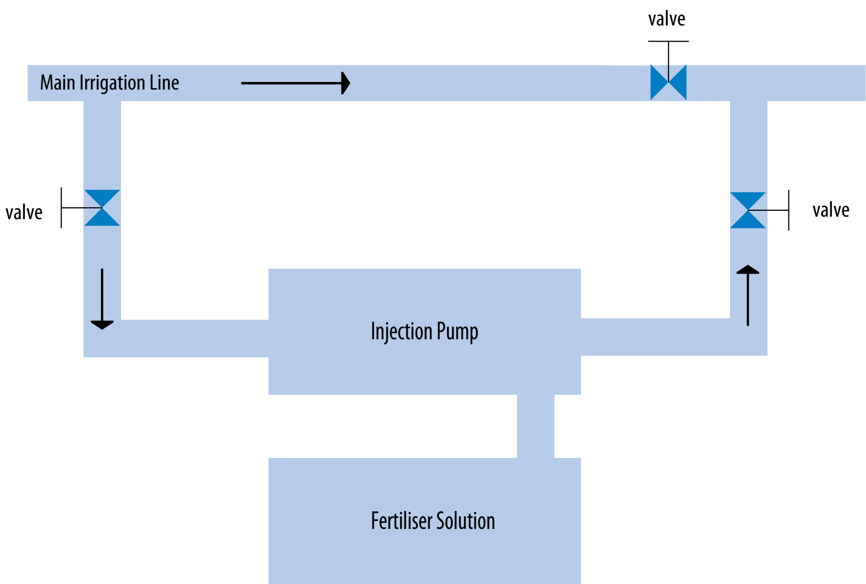


Figure 5.7.4. Schematic of a Positive Displacement (Direct Injection) system



Fertigation in Surface Irrigation Systems

For surface irrigation systems, water–run urea is the primary fertigation method used. The urea is added to the irrigation water at a point where it can dissolve and thoroughly mix before being applied to the field. This is usually at a culvert or drop structure in the supply channel or head ditch. There will be some loss of nitrogen to the channel and tailwater must be recirculated to minimise losses and off-field impacts. Research has shown similar recovery of water-run and soil–applied urea by cotton.

Water-run urea will be distributed through the profile with the irrigation water and is readily available for crop uptake. Water-run urea can be applied using the following methods:

- Applying urea to dry soil ahead of the irrigation event – losses can be high where urea is broadcast onto a moist soil surface
- N Buggy type equipment that delivers a measured weight of urea directly to the irrigation water flowing through an irrigation channel. The rate of fertiliser addition can be regulated according to flow rate.
- In some areas, urea solutions are available and can be delivered on-farm. A constant head tank containing a float-valve mechanism to maintain a constant flow of dissolved fertiliser into the channel is required. Changing the flow rate of the fertiliser solution or the irrigation water can vary the N application rate.

The uniformity of nitrogen application will be related to the uniformity of the irrigation event. It is possible to achieve furrow irrigation distribution uniformity in excess of 90%, in which case the application of nitrogen will be reasonably even along the field length. However, if the irrigation is not uniform, it is most likely that more nitrogen will be applied at the head ditch end of the field with less applied at the tail drain end.

Similarly, poor irrigation efficiency will lead to losses of nitrogen as well as water. Water lost below the root zone as deep drainage will take nitrogen with it. Whilst tailwater recycling will capture that nitrogen that leaves the field with the irrigation runoff, further nitrogen losses may occur in the on-farm storage.

Without knowledge of the efficiency and uniformity of the irrigation event in which water-run urea is applied, it is impossible to be certain of the amount of nitrogen that has actually been applied to the crop root zone. This makes precise nutrition management difficult.

Anhydrous ammonia should not be injected into irrigation water as considerable losses from volatilisation of ammonia can occur. Under windy conditions losses of 25% per hour have been recorded. This leads to uneven application and poor crop responses. Additionally, when anhydrous ammonia molecules (NH3) dissolve in water they are transformed into positively charged ammonium ions (NH4+). These are attracted to the negative charged clay particles in the soil. As a consequence, the ammonium ions may be removed from irrigation water near the head ditch rather than being distributed uniformly down the furrow. This is not a problem with urea which has no charge and is more evenly distributed with the irrigation water.

Most fertilisers are salts that dissolve when mixed with water and can be strongly adsorbed by the soil and organic matter, and may not be evenly distributed throughout the field and soil profile with applied irrigation. This is particularly important with zinc and phosphorus which is strongly held by the soil. Fertilisers of these nutrients should not be applied using water—run technology in surface irrigation systems.

Solubility

Not all fertilisers are suitable for fertigation as some are insoluble due to their chemical properties or manufacture.

As a rule of thumb the following chemical properties should be adhered to in determining the solubility of certain fertilisers:

A. All ammonium, nitrate, potassium, sodium and chloride salts are soluble.

B. All oxides, hydroxides and carbonates are insoluble.

C. All sulfates are soluble except for calcium sulfate.

Using these rules, calcium nitrate is soluble (rule A). Calcium carbonate and magnesium carbonate (lime & dolomite) are insoluble (rule B). Magnesium sulfate (Epsom salts) is soluble but calcium sulfate (gypsum) isn't (rule C).

Consideration also needs to be given to these rules of thumb when different fertilisers are mixed in solution and applied together as it is possible that a precipitate (sediment) may form. For example, if calcium nitrate and potassium sulfate are mixed together they separate and reform as potassium, nitrate and calcium sulfate (gypsum)

It is generally safe to mix: urea, muriate of potash, potassium nitrate and chelated trace elements.

Problem products: Phosphates; sulphates; calcium; magnesium and trace elements as insoluble reaction products may form in the mixing tank.

Due to the manufacture of certain fertiliser products and their purpose of use some contain insoluble impurities, coating agents or granulation:

- These impurities may block filters, emitters and potentially large sections of irrigation infrastructure (drip tape blocks)
- Some fertilisers that may be used in fertigation programs are coated. The coating agents are used to improve the handling characteristics as a dry solid before the products are used. When these products are dissolved in water the coatings begin to break down and may present problems with blockages of filters and small emitters.
- Some fertilisers have a coarse particle size and take a long time to dissolve.

Coarse, granular and prilled products can be used provided they do not contain excessive amounts of impurities but may require more agitation. To resolve this source soluble fine or solution grade products that dissolve more quickly

The maximum solubility of a fertiliser in water, while temperature dependent, is a physical constant. As a fertiliser solution becomes more concentrated it becomes increasingly difficult to dissolve more fertiliser. When no more fertiliser can be dissolved regardless of continual agitation the solution is at saturation point. Any remaining undissolved fertiliser has the potential to precipitate. Some fertilisers also cause the temperature of the solution to fall which reduces the solubility. e.g. urea, nitrates.

Fertilisers have different solubilities and therefore need different amounts of water to dissolve and should be completely mixed before being injected. This is where agitation plays an important role in the effectiveness of injection. Agitation is easier in vertical tanks as there is a smaller surface area at the base of tank. It is also essential that you test the mix for corrosion potential and deposition - phosphorous has high corrosion potential when used in galvanised iron which is a particular consideration for CPLM users.

Good agitation and a fine particle size results in a quicker dissolve rate, but the maximum concentration that's able to be dissolved does not change

Table 5.7.1. Solubility rating of various fertiliser products

Product	kg / 100 L@ 20° C	Product	kg / 100 L@ 20° C
Ammonium nitrate	192	Calcium nitrate	60
Ammonium sulphate	75	Magnesium sulphate	71
Mono-ammonium phosphate MAP	37	Magnesium nitrate	71
Liquifert P (Tech MAP)	20	Soluble boron	9.5
Mono-potassium phosphate MKP	12	Zinc sulphate	44
Potassium chloride	34	Liquifert K (KCl)	20
Potassium nitrate	8	Liquifert N (Urea)	25
Potassium sulphate	10	Urea (water temperature 5° C)	45

If you are considering applying two chemicals at once, test the compatibility with each other and with the irrigation water as a precipitate (sediment) may form. Manufacturers can help out here and are able to advise on the corrosion potential of their products.

Urea, muriate of potash, potassium nitrate & chelated trace elements are generally considered safe to mix. However phosphates, sulphates, calcium, magnesium and trace elements can create problems. When this happens the following can occur:-

- Precipitates may settle to the bottom of the tank or block filters and emitters.
- Precipitates may also form if the water is hard (i.e high in Ca and Mg or contains carbonate).

Therefore the trace elements to avoid are copper, zinc, manganese and iron sulphates. These cannot be mixed with calcium nitrate, MAP, MKP and always use chelated forms of trace elements if mixing products.

Table 5.7.2. Product compatibility chart

	Urea	Ammonium nitrate	Ammonium sulphate	Mono-ammonium phosphate MAP	Mono-potassium phosphate MKP	Potassium nitrate	Potassium sulphate	Potassium chloride	Calcium nitrate	Magnesium sulphate	Soluble boron
Urea		YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Ammonium nitrate	YES		YES	YES	YES	YES	YES	YES	YES	YES	YES
Ammonium sulphate	YES	YES		YES	YES	YES	YES	YES	NO	YES	YES
Mono-ammonium phosphate MAP	YES	YES	YES		YES	YES	YES	YES	NO	NO	YES
Mono-potassium phosphate MKP	YES	YES	YES	YES		YES	YES	YES	NO	NO	YES
Potassium nitrate	YES	YES	YES	YES	YES		YES	YES	YES	YES	YES
Potassium sulphate	YES	YES	YES	YES	YES	YES		YES		YES	YES
Potassium chloride	YES	YES	YES	YES	YES	YES	YES		YES	YES	YES
Calcium nitrate	YES	YES	NO	NO	NO	YES	NO	YES		NO	NO
Magnesium sulphate	YES	YES	YES	NO	NO	YES	YES	YES	NO		NO
Soluble boron	YES	YES	YES	YES	YES	YES	YES	YES	NO	NO	

The **options for applying Incompatible products** include:

- Apply the fertilisers at different times (e.g. apply MAP or MKP and sulphate fertilisers at different times to calcium fertilisers);
- Alternate between the products each time the crop is irrigated; and,
- use two mixing tanks and injectors - as the concentration of nutrients in the irrigation lines is very dilute and therefore there is less chance of precipitate formation.

System Performance

The performance of fertigation systems depends on the injection type used and the application system. Correct injection rates and an application system that applies water uniformly are crucial to ensure that the distribution of fertiliser is uniform and effective.

To ensure fertiliser is delivered to the field as required it is necessary to understand the hydraulics of your application system. Depending on the size of the irrigated property the application system may be in several components at which point it is beneficial to understand all delivery points. Essentially each irrigated field has an individual hydraulic characteristic.

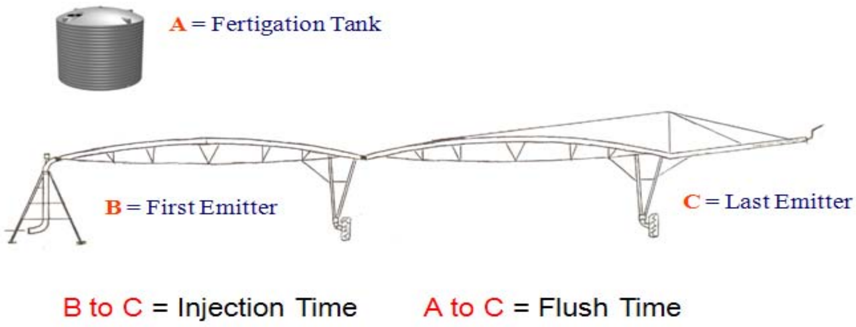
- The injection of the fertiliser should not start until the flow rate and pressure of the irrigation system reach their normal operating levels. For drip systems this may require running the system for up to one hour prior to commencing the injection.
- Check travel time of overhead irrigation systems and recalculate the fertiliser injection rate for the planned amount of fertiliser.
- Prevent back-flow from the irrigation lines into the water supply. This is more likely to occur where suction systems, on the inlet side of the pump, are used to introduce fertiliser solutions.
- Avoid injection into empty lines.
- With travelling irrigation systems, the fertiliser solution must be injected continuously at a constant rate (and concentration). For drip systems the fertiliser solution is usually injected in the middle half of the irrigation set time (to ensure the system has reached normal operating levels and for flushing of the system.
- After the fertigation process has started, recheck the fertiliser injection rate.
- Periodically revisit the irrigation system and recheck the operation of the injection meter, operating pressure of the system and water distribution of the irrigation system including the end gun operation on centre pivots.
- At the end of each fertigation application, continue running water through the irrigation system until all of the fertiliser has been discharged from the pipeline of the irrigation system. This will vary depending on the distance between the fertigation tank and the irrigation system. Also run clean water through the injection meter, chemical discharge hose and check valve. Flushing after use prevents scale forming and extends the life of gaskets and metals.
- Maintain a neat storage, mixing and injection area. This promotes safe handling and facilitates early recognition and clean up of any spills and leaks.
- Prevent drainage from the injection/storage area into streams, dams or bores.

Before any test is started, the system must be operating at its normal operational pressure. Once the system is running at the correct pressure commence injecting. There are many indicators to measure performance. Nitrate test strips can be used with a nitrate fertiliser. This is simple as you do not need much nitrate fertiliser in the tank for it to be effective. EC meters (salts), pool test kits (acid and chlorine), molasses and dyes can also be used to check the system.

Injection times and flushing procedure will vary between different irrigation blocks. Select the desired system to check and then start the injection process, being sure to make a note of the injection time (A).

Calculate the time it takes for the fertiliser to reach the first emitter/ sprinkler (A – B). If fertiliser injection is done at the actual centre pivot / lateral move/ drip system this time will be minimal but if the fertiliser is injected at the pump some distance away it can take quite a while to get there depending on the sizes of mains/sub-mains.

Now measure the time it takes to get from the first emitter/sprinkler to the last emitter/sprinkler of the centre pivot / lateral move/ drip system (A - C). For most centre pivot / lateral moves and drip systems this time is reasonably quick. Take a note of this time as this is relevant to your injection time at the fertiliser tank.



What do the times mean?

The duration of the fertiliser injection must take at least the same amount of time or longer than it takes for the fertiliser to move from the first emitter to the last emitter. If the injection duration is shorter then not all the areas in the irrigated field will receive the same amount of fertiliser. The uniformity of fertiliser will be uneven with parts of the crop receiving more than others.

Once the fertiliser is injected, the system needs to be flushed for the correct amount of time. This is the same as the time it takes for fertiliser to get from the tank to the last emitter/sprinkler. If the irrigation system is not left running for this time or longer, fertiliser will remain in the main/sub-mains and not be correctly distributed in the block. Worse still you will leave fertiliser (salt) inside the centre pivot/lateral move where it can cause corrosion. It can also block emitters in drip systems particularly if other products are used in subsequent irrigations.

For large irrigation systems such as centre pivots and lateral moves the ability to track fertiliser movement may be difficult given high flow rates.

An alternative to direct measurement is to complete a velocity of flow calculation using the following calculation:

Velocity (m/sec) = $1.274q / d^2$
where
q = Volume flow (m^3/sec)
d = pipe inside diameter (m)

Example
8″ pipe and a flow rate of 100 L/sec
8″ = 200mm = 0.2m
100 L/sec = 0.1 m^3/sec

Thus,
V = (1.274 x .1) / 0.22
V = (0.1274) / 0.04
V = 3.185 m/sec

This velocity can be used to estimate the time taken for fertiliser from the injection point to leave the system. If the distance from the injection point to the end of the overhead system is 1000 m then the time taken will be 314 seconds or 5 minutes and 14 seconds (1000 m ÷ 3.185 m/sec).

Application tips

The following application tips are provided with the objective of preventing contamination of nearby water sources, occupational health and safety and handling practices.

- Maintain a neat storage, mixing and injection area. This promotes safe handling, and facilitates early recognition and clean-up of any spills and leaks.
- Prevent drainage from the mixing area into streams, dams or bores.
- Prevent back-flow from the irrigation lines into the water supply. This is more likely to occur where suction systems, on the inlet side of the pump, are used to introduce fertiliser solutions.
- Allow excess water to re-enter reticulated water supplies for use on other irrigated fields where the same crops are grown. Livestock should be denied access to tail-water, to avoid any risk of urea or nitrate poisoning. This is also important for other reasons, e.g. it is particularly important if pesticides have been used for which a nil MRL (Maximum Residue Level) applies to livestock products,
- Prepare fertiliser solutions as close as possible to the time of use. Do not allow to stand for an extended period of time, e.g. Over night. This can help minimise precipitation and settling in mixing tanks in some instances.
- Inject fertiliser solutions upstream of filters, so that insoluble contaminants are screened out.
- Flush injectors and lines after use, to minimise corrosion and scale formation, and extend the life of gaskets.

Further Reading

Centre pivot and lateral move machines in the Australian cotton industry by J.P. Foley and S.R. Raine (2001). NCEA Publication 1000176/1

Fertigation Fact sheet, Growcom Australia, Water for Profit, www.growcom.com.au

Methods of Fertigation Fact sheet, Growcom Australia, Water for Profit, www.growcom.com.au

Measuring Fertigation System Performance Fact Sheet, Growcom Australia, Water for Profit, www.growcom.com.au

Incitec Pivot Limited Agritopic Fertigation, 2004

Incitec Pivot Limited Fertigation with Moving Irrigation Systems

Section 6

A significant amount of catchment scale work which has been undertaken over the last few years has not yet been incorporated into WATERpak. This work has been summarised in the Australian Cotton Water Story publication and will be incorporated into a future edition of WATERpak.

Catchment-scale impacts

6.1 Case study, catchment water quality and cotton: northern NSW

Warwick Mawhinney
DIPNR, Tamworth

Key points

- Since monitoring of pesticide residues in surface water began in 1991, the most commonly detected insecticide has been endosulfan.
- Restrictions on endosulfan use, and further emphasis on the cotton industry's integrated pest management system (IPM), best management practice strategies and the introduction of genetically modified and insect tolerant cotton varieties, have resulted in a reduction in the detection of endosulfan residues.
- Atrazine is the most commonly detected herbicide and since 1992 the most commonly detected pesticide in groundwater is atrazine. Atrazine is not used for cotton production and is more commonly used in dryland grain crops.
- Irrigators should monitor the quality of the water that they pump into storages to ensure they are not salinising their own land.
- Some degree of contamination of surface and groundwater will always occur in agricultural areas. Our common aim should be to minimise the impact.

Australia is a dry continent, and we are all aware of the value of good quality water. It protects public health, supports economic production and maintains a healthy river ecosystem. Water quality is largely determined by land use, geology, climate, riparian vegetation and stream flow.

Alteration of the landscape since European settlement has resulted in marked changes in catchment conditions. Since then, land use has had an increasing impact on water quality. Agricultural activities such as land clearing, broadscale cultivation, irrigation and grazing can increase levels of turbidity, salinity, nutrients and pesticides in our waterways.

Water quality within cotton-growing regions of northern NSW is being monitored by DIPNR. These results show the levels of insecticides (in particular endosulfan) are decreasing, while herbicides continue to be detected at numerous sites throughout the region.

A review of water quality in rivers of North-West NSW

The Central and North West Regions Water Quality Program (CNWRWQP) was jointly funded by the then Department of Land and Water Conservation and the water users of the Macintyre, Gwydir, Namoi and Macquarie valleys. The project commenced in the early 1990s and focused on the impacts of agriculture on water quality. Nutrients, salinity, turbidity and up to 34 agricultural chemicals were monitored, at a number of sites, over a ten-year period.

Pesticides

The detection of pesticides (including insecticides, herbicides and defoliants) in surface water is of great concern to water managers and the community as a whole, as the effects of long-term, low dose exposure of humans and the environment to pesticides are largely unknown.

Spray drift, vapour transport and run-off are the main pathways for pesticide transport into river systems (Mawhinney 1998, Raupach et al. 2001). Spray drift and vapour both contribute low level but almost continuous inputs to the riverine ecosystem during the peak spraying season. Spray drift occurs when pesticide droplets, while still in the air, move away from the target area into neighbouring environs. The likelihood of pesticide drift is influenced by weather conditions, the method of application, equipment used and crop structure. Therefore it is important that these factors be considered before spraying.

Run-off tends to provide occasional high concentrations of pesticide contamination. Pesticides in run-off can be dissolved in the water, bound within sediments or adsorbed onto suspended particles. One way to reduce the amount of pesticides in our river systems is to minimise run-off from agricultural land and associated sheet, rill, gully and stream bank erosion. Research by Rosewell (1988) has shown that the amount of run-off from even a short fallow is increased five times, compared to pasture, while soil erosion is magnified by a factor of eight to 20 times. Poor soil structure increases run-off and erosion. The pulverising effects of cultivation and the loss of organic matter are the two factors that most disrupt the soil structure in agricultural systems.

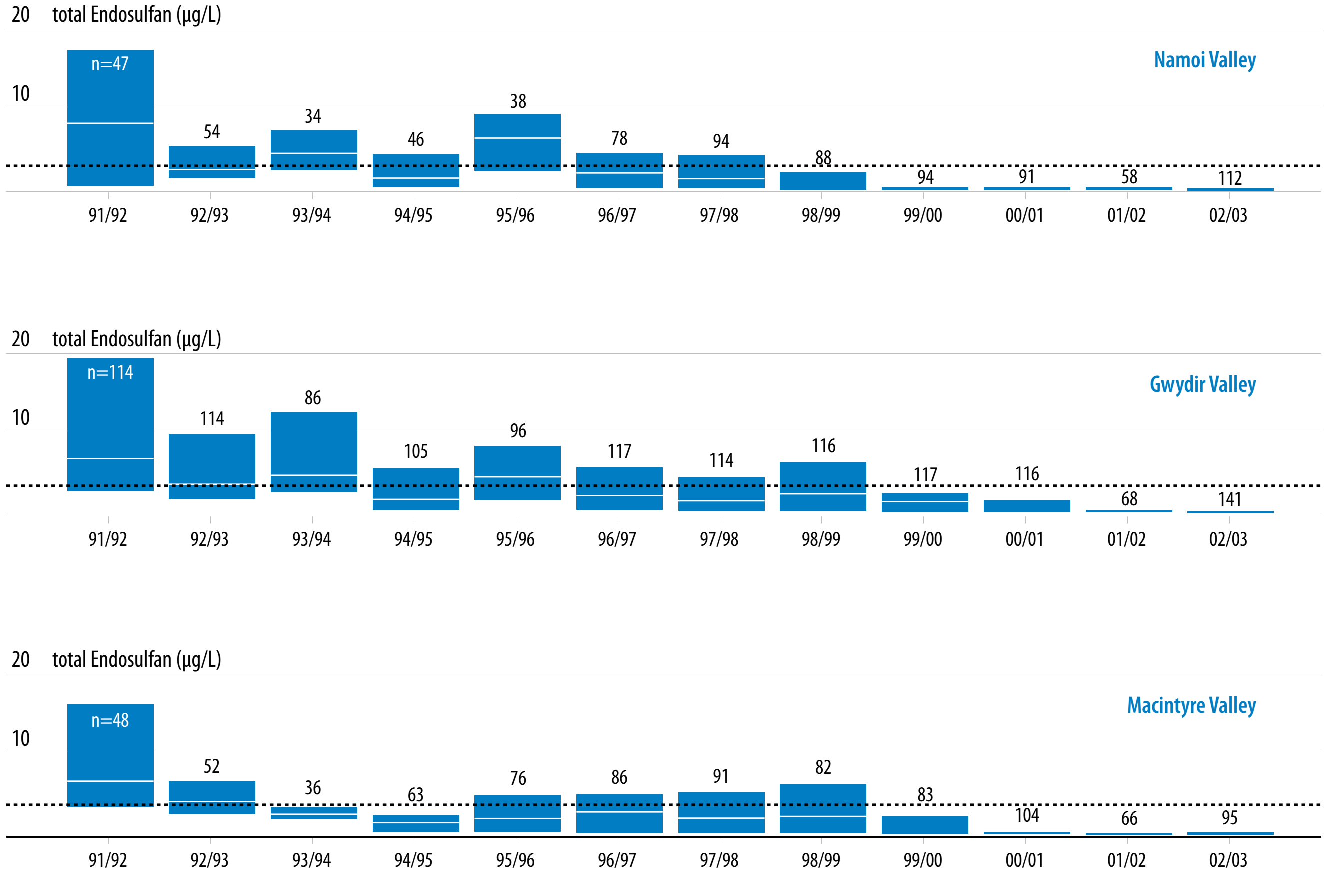
The pesticides that were regularly detected through the CNWRWQP in the Namoi, Gwydir and Macintyre valleys, and the number of detections in each sampling year, are given in Table 6.1.1. The number of samples includes all sampling sites across each valley, not just those located in the main cotton-growing areas.

Table 6.1.1: Number and percentage of detections of common pesticides for all samples collected across all sites in the Namoi, Gwydir and Macintyre valleys from 1991/92 through to 2002/03

	Endosulfan	Atrazine	Diuron	Fluometuron	Metolachlor	Prometryn	Simazine	No. samples
1991/92	174 (59%)	136 (46%)	60 (20%)	16 (5.4%)	0	41 (14%)	ns	296
1992/93	194 (65%)	113 (38%)	28 (9.4%)	17 (5.7%)	0	32 (11%)	ns	299
1993/94	137 (65%)	71 (34%)	28 (13%)	19 (9.0%)	14 (6.7%)	15 (7.1%)	ns	210
1994/95	135 (48%)	106 (38%)	27 (9.6%)	10 (3.6%)	2 (0.7%)	12 (4.3%)	ns	281
1995/96	169 (58%)	178 (61%)	14 (4.8%)	2 (0.7%)	25 (8.6%)	23 (7.9%)	0	291
1996/97	207 (52%)	138 (35%)	24 (6.0%)	32 (8.1%)	21 (5.3%)	39 (9.9%)	0	395
1997/98	196 (49%)	86 (21%)	40 (10%)	70 (17%)	37 (9.2%)	48 (12%)	3 (0.7%)	404
1998/99	182 (46%)	131 (33%)	79 (20%)	73 (18%)	53 (13%)	31 (7.8%)	8 (2%)	400
1999/00	126 (31%)	177 (43%)	75 (18%)	66 (16%)	58 (14%)	35 (8.5%)	2 (0.5%)	413
2000/01	76 (17%)	184 (42%)	57 (13%)	86 (20%)	59 (14%)	25 (5.7%)	18 (4.1%)	438
2001/02	14 (4.8%)	81 (28%)	28 (9.7%)	21 (7.2%)	15 (5.2%)	17 (5.9%)	18 (6.2%)	290
2002/03	4 (1.1%)	69 (20%)	27 (7.8%)	18 (5.2%)	9 (2.3%)	10 (2.9%)	3 (0.8%)	348

ns = not sampled

Figure 6.1.1. Box plots of total endosulfan results by river basin from 1991/92 to 2001/02



The broken line represents the Australian and New Zealand water quality guideline trigger value (ANZECC and ARMCANZ 2000) for 99% ecosystem protection (0.03 µg/L). Each box represents the middle 50% of the data collected for each year. The middle line in each box represents the median (or 50th percentile) value, which is the most useful when assessing water quality data.

The most commonly detected insecticide in north-west NSW from 1991 to 2002 was endosulfan. From 1991 to 1999, about 50% of samples contained residues of endosulfan (Table 6.1.1). Endosulfan concentrations in the Namoi, Gwydir and Macintyre valleys from 1991 to 2002 are given in Figure 6.1.2. A similar contamination pattern is visible in all three valleys. The highest level of contamination by endosulfan occurred in the 1991/1992 growing season. This coincides with the rapid expansion of the cotton industry and a relatively low awareness of best practice methods compared to today's standards. Levels dropped in 1994 and 1995 in response to the drought, as the area sown to cotton was greatly reduced, so that the amount of endosulfan applied was significantly less than previous years.

In 1998/1999 endosulfan residues were detected in cattle. The result was the introduction of greater restrictions on endosulfan use, and further emphasis on the cotton industry's best management strategy. Figure 6.1.1 shows how these two factors resulted in a dramatic reduction in endosulfan in the three valleys during 2000/2001 and 2001/2002. For the first time in ten years endosulfan residues were not detected in the Namoi River during the 2001/2002 spray season. The endosulfan monitoring results are also compared to the Australian and New Zealand guidelines for fresh and marine water quality (ANZECC and ARMCANZ 2000) trigger value for 99% ecosystem protection (0.03µg/L) as shown by the dashed line in Figure 6.1.1. The 99% ecosystem protection level means that 99% of species are expected to be protected if the concentration remains below the trigger value. Only in recent years have endosulfan concentrations fallen below the guideline level across all three valleys.

Other insecticides detected through the CNWRWQP were chlorpyrifos, profenofos, dimethoate, propargite and parathion. The detection of these insecticides was more sporadic than that of endosulfan, due to different chemical properties and generally lower usage rates. However Muschal and Warne (in press) have demonstrated that occasional high concentrations of chlorpyrifos and profenofos can have a deleterious impact on the aquatic environment.

The broken line represents the Australian and New Zealand water quality guideline trigger value (ANZECC and ARMCANZ 2000) for 99% ecosystem protection (0.03 µg/L). Each box represents the middle 50% of the data collected for each year. The middle line in each box represents the median (or 50th percentile) value, which is the most useful when assessing water quality data.

The most commonly detected herbicide through the CNWRWQP was atrazine (this includes the active ingredient and the two major breakdown products hydroxy-atrazine and desethyl-atrazine). From 1991 to 1999, as many as 61% of samples contained atrazine or one of its breakdown products. Table 6.1.1 shows that, in most cases, the percentage of samples containing pesticide residues dropped in 2001/2002. Other herbicides detected were diuron, fluometuron, metolachlor, prometryn and simazine. Metolachlor was most commonly detected in the Namoi Valley, while diuron, fluometuron and prometryn were more commonly detected in the Gwydir Valley. Little is known regarding the long-term impacts of herbicides on river ecosystems.

Salinity

Most landholders are well acquainted with the term salinity. Salinity is the presence of dissolved salts in soil and water and is a problem common to many parts of Australia. It may be caused by the presence of salt in underlying soil or bedrock, salt deposited due to past marine inundation of an area, or salt carried over the land surface from the ocean. Changes in land use can make this salinity problem worse. The replacement of native trees and grasses with annual crops and pastures, overgrazing and long fallows has increased the amount of water entering the watertable. During times of low rainfall, as the watertable falls, salts are concentrated in the soil. These salts can then be flushed into streams by run-off. Some streams may also be fed directly by saline groundwater. The most saline creeks and rivers in north-west NSW are located in the mid to upper parts of the catchment. Prolonged irrigation with saline water can exacerbate soil salinisation by providing salts in addition to those already present in the soil profile. Irrigators should monitor the quality of the water that they pump into storages to ensure they are not salinising their own land.

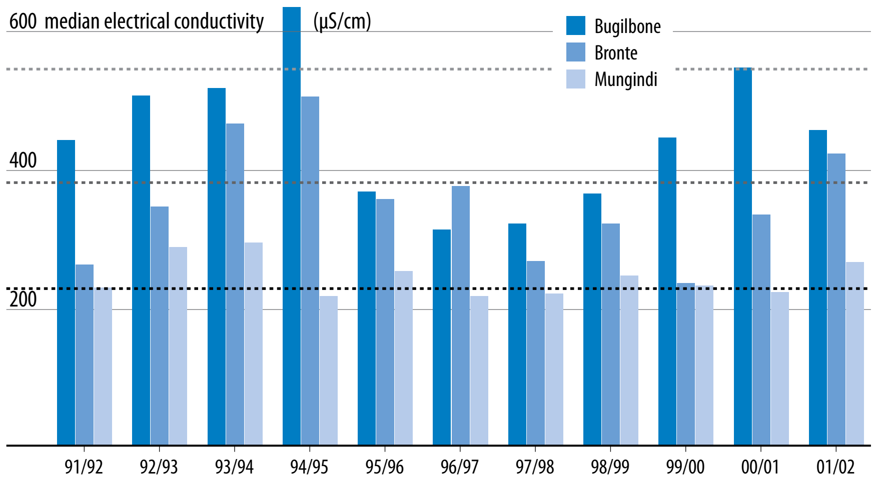
The most common measurement of salinity is electrical conductivity (EC), measured in microsiemens per centimetre (µS/cm). Electricity is conducted more easily (and therefore EC rises) as the concentration of dissolved salt increases. Figure 6.1.2 shows the median electrical conductivity at three sites, Namoi River at Bugilbone, Mehi River at Bronte and Barwon River at Mungindi, which are all located at the lower end of the major cotton-growing areas in each valley. In most years the Namoi Valley had the highest median electrical conductivity readings, while the Barwon River at Mungindi was consistently lower. The fluctuations from year to year are largely due to changes in flows due to rainfall, run-off and releases from storages.

The Australian and New Zealand water quality guidelines (ANZECC and ARMCANZ 2000) classify water with an electrical conductivity of less than 650 µS/cm as a very low salinity rating and being suitable for irrigating sensitive crops. These guidelines also provide trigger values, which are alert levels above which action should be taken to assess if there is potential impact on aquatic ecosystems. The generic trigger value for electrical conductivity in western NSW lowland rivers is 300 µS/cm.

In addition to this trigger value, the Catchment Management Board Blueprints have set specific end-of-system salinity targets for the Namoi (550 µS/cm), Gwydir (390 µS/cm) and Border Rivers (230 µS/cm) catchments. The blueprints specify that these targets for each valley should not be exceeded more than 50% of the time. Since 1991, the Namoi River at Bugilbone reached or exceeded the valley target four times and the Barwon River almost always reached or exceeded its target over the ten-year sampling period (Figure 6.1.2). Increased end-of-system salinity levels appear to be linked with low flows, as concentrations rose during the drought period of 1992 to 1995 and again in 2000 to 2002.

Figure 6.1.2. Median electrical conductivity (µS/cm) for three sites (Namoi River at Bugilbone, Mehi River at Bronte and Barwon River at Mungindi) located downstream of major cotton-growing areas and other land uses in each valley from 1991/92 through to 2001/02

Lines indicate Catchment Management Board salinity targets for the Namoi (----), Gwydir (----) and Border Rivers (----).



The phosphorus and nitrogen levels in the Namoi, Gwydir and Macintyre valleys are not limiting to algal growth. This means there are ample nutrients available in the water for the formation of algal blooms when conditions are favourable. Every year we see algal blooms in the large storages in the region, usually over summer, and blooms in the Barwon-Darling have been well documented.

Nutrients

Sources of nutrient contamination include sewage treatment works, farm effluent, run-off from agricultural land, septic tanks, industrial effluent and urban storm water run-off. Phosphorus and nitrogen are the main nutrients of concern. Similar to pesticides, phosphorus and nitrogen can be dissolved in water, bound within sediments or adsorbed onto suspended particulate matter (for example, soil or organic matter). In north-west NSW, run-off from agricultural land is the main source of nutrients, with the movement of nutrients attached to suspended material the main transport mechanism.

High concentrations of nutrients are important factors in the formation of blue-green algal blooms. Nutrient levels do not actually trigger an algal bloom, but determine how large the bloom becomes. Other factors such as water temperature, turbidity and water turbulence are also important. Blue-green algae can contain toxins which may cause severe dermatitis and conjunctivitis in people coming into contact with the algae through swimming or showering, and may cause stomach cramps, nausea, fever and headaches if consumed. Blue-green algae can also produce toxins that attack the liver and other internal organs and can act as neuromuscular blocking agents, leading to respiratory arrest (Chorus and Bartram 1999). Stock deaths in north-west NSW have been attributed to water contaminated by toxic blue-green algae.

Off-farm impacts

Bowmer et al. (1995) and Napier et al. (1998) reviewed NSW and Queensland fish kill registers and media reports between the mid 1970s and 1995. Bowmer et al. (1995) concluded that '*despite all the difficulties in assessing the evidence, it is still clear that cotton pesticides are causing the majority of those fish kills that have been reported, and that endosulfan is the pesticide most often implicated*'. Napier et al. (1998) concurred with this conclusion. An assessment of risk posed by pesticides to aquatic biota in rivers by Muschal and Warne (in press) determined that atrazine, diuron, fluometuron, metolachlor and prometryn posed either a low or moderate hazard to aquatic organisms. Their results also indicated that chlorpyrifos, endosulfan and profenofos posed a genuine risk to aquatic biota from acute exposures (brief exposure at high concentrations), and endosulfan also posed a risk from chronic exposures (continued exposure over a long period).

As endosulfan concentrations in the rivers have fallen in recent years, so too have the number of reported fish kills. Agricultural chemicals are not the only cause of fish kills: they can also be caused by the dramatic decline in water quality due to the 'first flush' effect. Many floods commence with an event characterised by high levels of sediment and nutrients at the very beginning of water levels starting to rise. This is often due to the sudden disturbance of the stream bed, and the purging of nutrients and poorly oxygenated water from standing pools. It is the toxic effect of these high concentrations of pollutants and low dissolved oxygen that appears to be the cause of recent fish kills, rather than chemical contamination. An example occurred in the Barwon River at Banarway Crossing in December 2002. In this instance a 'fresh' in the Moonie River flushed turbid, nutrient-rich and oxygen-depleted water into the Barwon River, resulting in more than a thousand dead fish.

Groundwater quality

Long fallowing, low water-use cropping and clearing of native vegetation have contributed to shallow, saline watertables, by increasing deep drainage of water through the soil profile. Shallow saline groundwaters can contribute to soil salinisation and can also leak downwards, contaminating deeper aquifers used for irrigation. This process is likely where excessive extraction causes long-term drawdown of groundwater levels. Consequently, groundwater quality and quantity issues are closely related, with hydraulic linkages meaning that maintaining good quality groundwater involves total groundwater management (Timms 1998).

Pesticides have been detected in groundwater in many different locations (Jiwan and Gates 1994a, 1994b, 1995; Timms 1997), with detections having a patchy and localised distribution. Since 1992 the most commonly detected chemical has been atrazine. Heavy black clays and proximity to cropping appears to be the major determinant for groundwater contamination by pesticides (Timms 1997). Observations in the field suggest that groundwater contamination by atrazine generally occurs in close proximity to sorghum crops. Atrazine has high water solubility, suggesting the predominance of diffuse contamination pathways through the soil profile. Isolated cases of low level contamination by diuron, fluometuron, metolachlor, simazine and trifluralin have also been found.

In addition, the contamination of bores by residues from abandoned chemical drums has been highlighted as a point source for chemical contamination. Chemicals with low water solubility and low mobility (for example, trifluralin) have been detected in such bores. Chemicals can leak directly into aquifers via backflow down the bore if drums are abandoned near poorly constructed bore heads, or during mixing and rinsing. The absence or poor maintenance of cement-lined mixing bays next to bores means that excess mixing waters drain into depressions close to or around the bore head and percolate directly to groundwater. This problem of point-source contamination is easily prevented with better farm management practices.

Once a pollutant enters an aquifer, depending on local groundwater conditions, it may either degrade, absorb onto aquifer materials or be transported laterally with groundwater flow. Unfortunately it is difficult to determine which mechanism is predominantly responsible for decreasing pesticide concentrations over time. Once an aquifer is contaminated either by chemicals or salinity, remediation of the aquifer is very difficult and very expensive. Prevention of aquifer contamination is strongly recommended.

Options to reduce the transport of pollutants off-farm

Improved surface and groundwater quality is possible, and the options to achieve it are not new. Most of the surface water quality problems are related to run-off. This is where improvements to land management and farming practices in a catchment area will achieve the best results. If run-off can be reduced, filtered by vegetation or stored on-farm, and then used before it can leak through the soil profile into shallow groundwater, many of the water quality problems could be solved.

The issue of groundwater contamination is complicated, mainly due to the lack of knowledge on agricultural chemical pathways through the soil profile. However, identified point sources of pollution, such as chemicals backflowing down bores and the over-extraction of deeper aquifers, can be addressed.

It must be remembered that some degree of contamination of surface and groundwater will always occur in agricultural areas. Our aim should be to minimise the impact. Management options that will achieve this goal include:

Adoption of best land, soil and vegetation management practices:

- maintaining at least 70% ground cover to reduce run-off and erosion;
- management of run-off through tailwater retention and prevention of tailwater releases (for example, 'blow outs');
- good soil management to improve organic matter content and soil structure; and
- good agronomic practices (for example, spray at optimum time, use certified seed).

Riparian vegetation management:

- exclude livestock from vegetated buffer strips along all creeks, rivers and major drainage lines (except for 'crash grazing', that is, a short period of intense grazing to keep rank growth in check, but not long enough for the animals to cause any damage along the riverside)
- install constructed watering points in stable areas to minimise streambank erosion and nutrient inputs by livestock
- maintain vegetated buffer strips down slopes of cropped paddocks and vegetated waterways to intercept and filter run-off water and minimise spray drift
- on-going maintenance of bore heads to prevent groundwater contamination by pesticides
- use of best management practices for chemical application to minimise the transport of chemical off-farm.

Water quality guidelines

For more information on National Water Quality Guidelines, see the following internet sites.

Guidelines for fresh and marine water quality **www.erin.gov.au/water/quality/nwqms**

Australian Drinking water guidelines **www.health.gov.au/nhmrc/publications**

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6.2 Case study, water quality in the Gwydir Valley watercourses

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Introduction

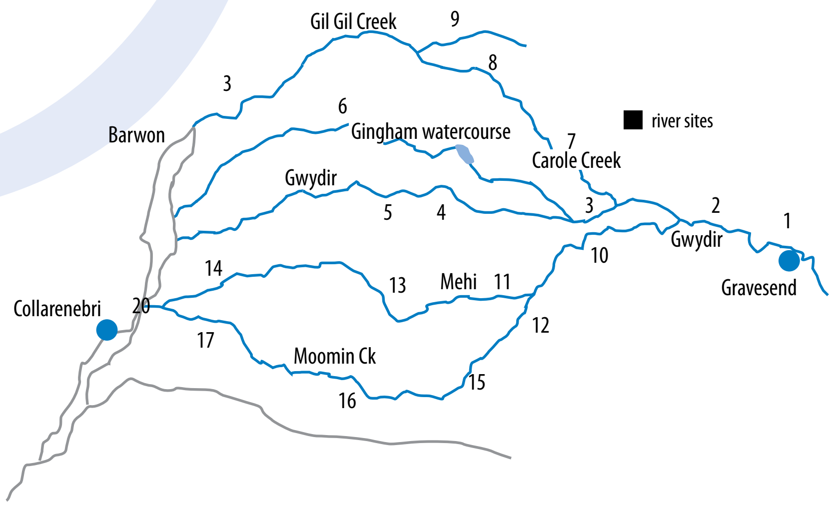
Irrigators are frequently accused of causing a deterioration of water quality in the Murray Darling Basin. For many catchments, such as the Gwydir in north-west NSW, little reliable information is available to assess the impact of irrigation on water quality.

The aim of this research is to measure the water quality (in terms of sediment, salts and nutrients) of the Gwydir Valley watercourses. By monitoring water quality above, within and below the irrigation area, any changes in water quality within the irrigation area can be examined to determine the impact of irrigation. Water quality data were also combined with river flow data to determine the quantity (load) of sediments, salts and nutrients that may leave the Gwydir Valley and enter the Murray Darling Basin.

Methods: Location

The Gwydir Valley River Catchment is located in north-west NSW. The Gwydir Catchment covers an area of approximately 26500 km^2 and is a part of the Murray-Darling Basin. Water from the Gwydir River supports a major irrigation industry, with 86,000 hectares licensed for irrigation. Water from Copeton Dam is delivered to irrigators whose farms are located along the Gwydir, Carole, Mehi and Moomin watercourses.

Figure 6.2.1. Location of water sampling sites (sampling Site 10 is Moree)



Sampling commenced in October 1998 and continued until July 2001. Water samples were collected weekly over summer, fortnightly during March, April, October and November, and monthly during the remainder of the year.

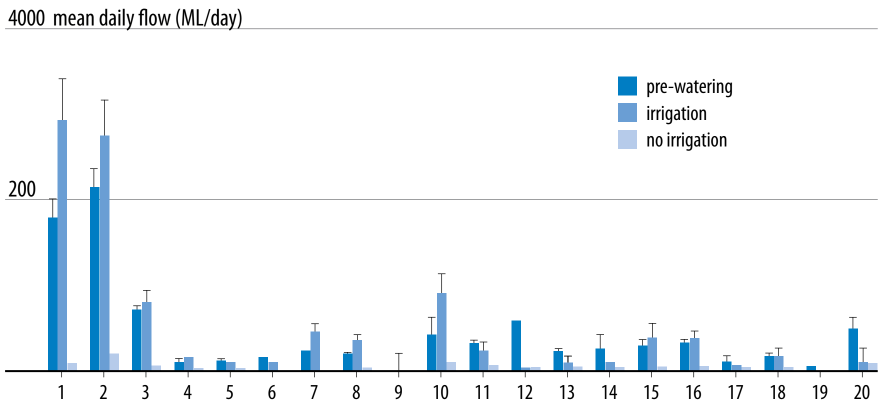
Results and discussion

Flow

Figure 6.2.2 shows the median daily flow at each sampling site, during each flow phase. The error bars represent the standard error of the median. Site 1 (Gravesend), Site 2 (Pallamallawa), Site 3 (Yarraman) and Site 10 (Moree) have a significantly higher flow compared to other sites within the valley. Site 1, located upstream of the irrigation area, has a median daily flow of 2950 ML/day during the irrigation phase, compared with Site 18 and Site 20, located downstream of irrigation area, which have median daily flows of 168 ML/day and 90 ML/day respectively. This difference in flow between the upstream and downstream sites is because the Gwydir has not yet split into the Mehi and Carole anabranches at the upstream sites. The flows decrease through the valley as the Gwydir splits into these anabranches and with the extraction of water for irrigation and stock and domestic supplies, along with evaporation and seepage losses. Furthermore, environmental flows from natural rainfall upstream or releases from Copeton Dam are accounted for in the flows at Site 1 and Site 2, but have no impact on flows at Site 18 and Site 20, as this water is directed straight down the Gwydir and Gingham watercourses (see Figure 6.2.1).

Flow during the pre-watering and irrigation phases are significantly higher than the no-irrigation phase with the release of water from Copeton Dam for irrigation purposes along with the increased likelihood of summer storms.

Figure 6.2.2. Median mean daily flow for each river site, during each flow phase (No 10 = Moree)



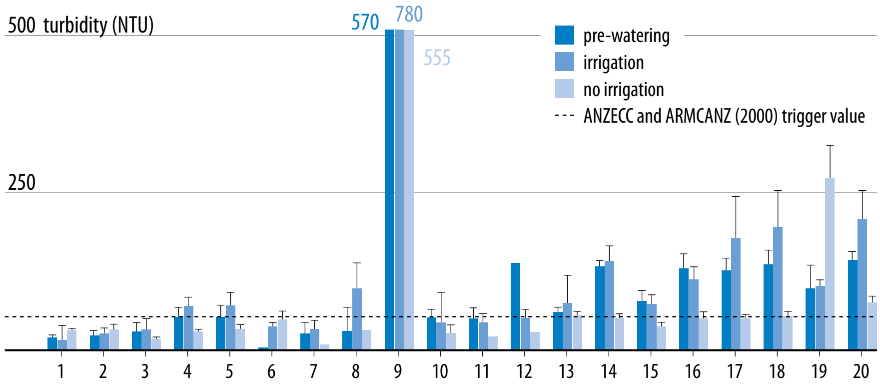
Turbidity

Median turbidity of all sampling sites within each flow phase is presented in Figure 6.2.3. All sites located downstream of Site 10 (Moree) exceed the ANZECC & ARMCANZ (2000) water quality guidelines for protection of aquatic ecosystems (50 NTU) and irrigation water (100 NTU). Median turbidity increases along the valley, with the highest median values at sites located at the bottom of the valley, Site 17 (Iffley), Site 18 (Galloway) and Site 20 (Collarenebri). This is a reflection of the cumulative effects of land use, streambank erosion and resuspension of sediments through the valley.

The turbidity of water at Site 9 is significantly higher than all other sites within all flow phases. This site is before any irrigation and is unregulated, and so only flows after run-off in the local catchment. Run-off, which causes soil erosion and therefore the transportation of particulate matter into the waterways, is a major contributor to turbidity.

High turbidity at sites lower in the valley reflect not only farming practices carried out on irrigated lands, which account for less than 4 per cent of the Gwydir Valley (North West Catchment Management Committee, 1997), but also land use practices associated with dryland farming (26 per cent), grazing (58 per cent of the Gwydir), timber (12 per cent) and other land use activities (<1 per cent) along the valley.

Figure 6.2.3. Median turbidity for each river site

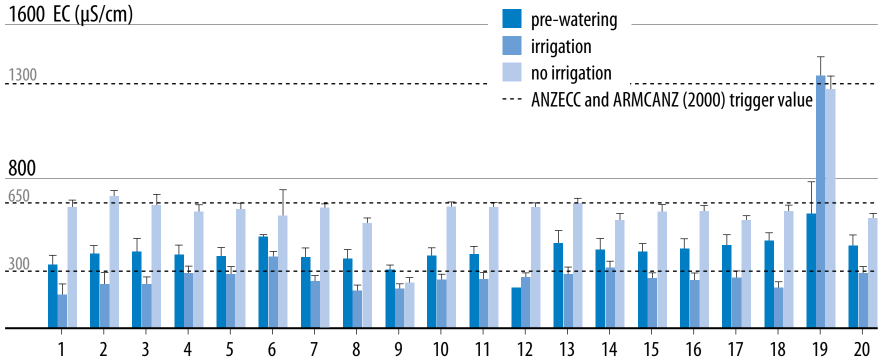


Irrigators are required to contain all water (run-off and tailwater) on-farm. Farms are designed to collect any water that runs off the fields and this water is stored in on-farm storages, which can be recirculated and used as irrigation water at a later date. Therefore, in theory, there should be no water coming off irrigation farms, and thus no input of sediments, salts and nutrients. However, during severe flood events, when farmers exhaust all water-holding infrastructure, or during a collapse of irrigation infrastructure (channels, banks or storages), some water could be released off-farm and make its way into the river system. It should be noted that, during such a flood event, the water spreads over the vast flood plains, making it impossible to determine the source of the sediments, salts and nutrients.

Salts

Median electrical conductivity (EC) mostly exceeded the ANZECC & ARMCANZ (2000) water quality guidelines for protection of aquatic ecosystems (>300 µS/cm), especially during the no-irrigation phase (Figure 6.2.4). EC has a significant negative correlation with flow (Nancarrow 1998), where an increase in flow causes a dilution of ions in solution, resulting in a decreased EC. Therefore, EC is significantly lower during the pre-watering and irrigation phase when flows are significantly higher. Most of the flow during January and February (irrigation phase) comes from releases of water from Copeton Dam. Gordon (2001) found Copeton Dam water to have a low EC and releases from Copeton to have a major influence on EC in the Gwydir river system throughout the year 1999/2000.

Figure 6.2.4. Median electrical conductivity



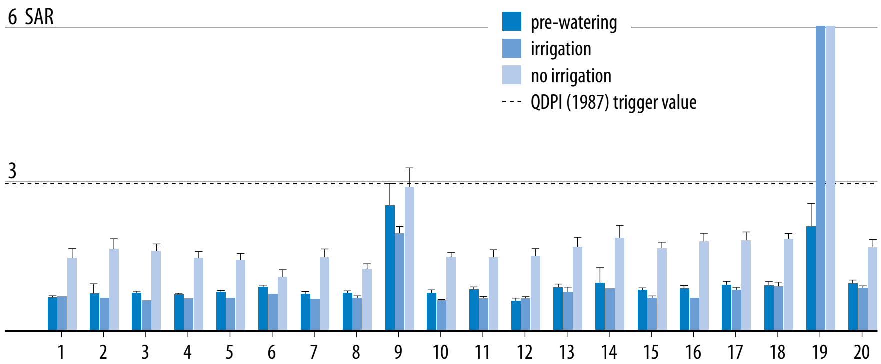
Median EC for all sites except Site 19 were classed with either a low (650–1300 µS/cm) or very low (<650 µS/cm) salinity rating for irrigation water. The EC at Site 19 is significantly higher than all other sites. This site is located at the end of the Gwydir River, where water only reaches during flood events, thus only flowing during flood events or local, run-off-producing rainfall events. It is a stagnant pond of water for most parts of the year where salts and nutrients accumulate and become concentrated due to the lack of fresh water flows, resulting in a high EC.

It can be seen that there is no significant increase in salinity moving downstream, indicating that irrigation is not influencing salinity in the rivers. Also, the release of irrigation water from Copeton Dam improves the salinity situation in the river due to the dilution effect causing a decrease in EC.

The median SAR for all sites within each flow phase are presented in Figure 6.2.5. The median SAR for all sites except Site 19 fall within a non-sodic classification (<3).

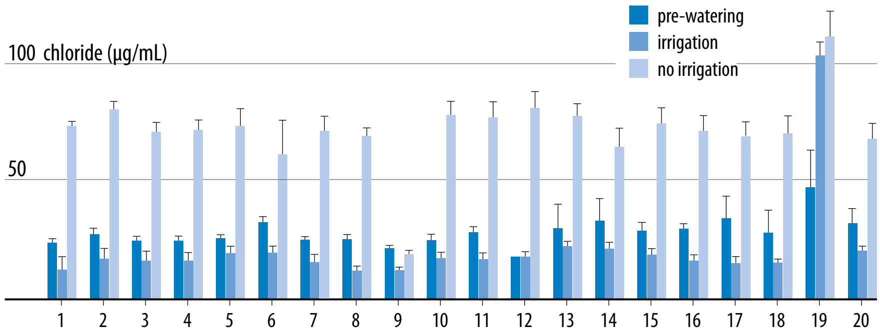
There is no significant difference between electrical conductivity (EC) and the sodium adsorption ratio (SAR) between the upstream (Site 1 and Site 2) and downstream sites (Site 18 and Site 20) within any of the flow phases.

Figure 6.2.5. Median SAR



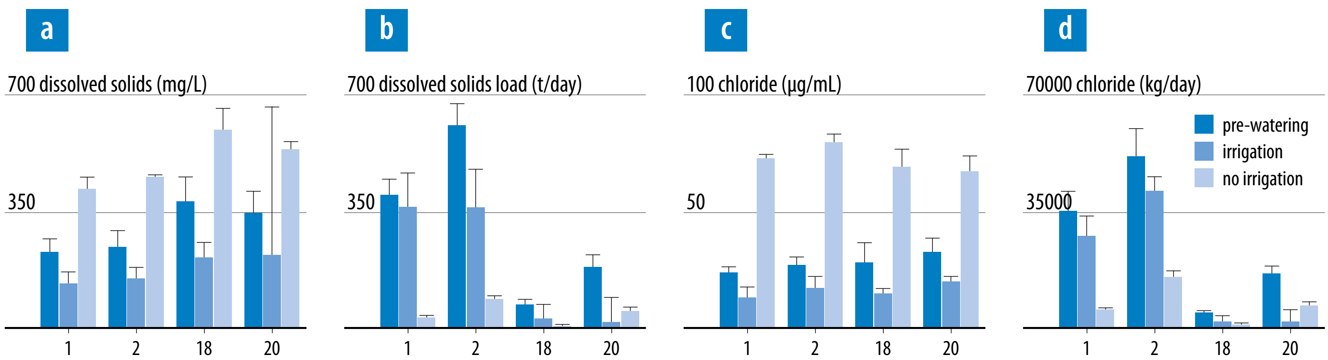
Chloride levels at all sites fall below the level of chloride affecting sensitive crops (<175 mg/ml) as shown in Figure 6.2.6. Chloride levels are significantly higher during the no-irrigation phase, as a result of the low flows during this phase.

Figure 6.2.6. Median chloride concentration for each river site, during each flow phase



Total dissolved solids (TDS) concentration is used as an estimate of salt concentration and consequently salt loads. Although there is no significant difference in salt concentration between the upstream and downstream sites, salt loads are significantly higher upstream as shown in Figures 6.2.7a and 6.2.7b. The median load of TDS during the irrigation phase for Site 1 was 353 tonnes/day, whereas a median of only 35 tonnes/day flowed past Site 18, and 23 tonnes/day flowed past Site 20 in the same year. Again, although there is no significant difference in chloride concentration between the upstream and downstream sites, the loads of chloride (kg/day) are significantly higher upstream as shown in Figures 6.2.7c and 6.2.7d. The load of chloride in the water decreases, with reduced flows downstream in the Gwydir Valley. The median load of chloride during the irrigation phase for Site 1 was 27 tonnes chloride/day, whereas less than 2.5 tonnes flowed past both Site 18 and Site 20 in the same year.

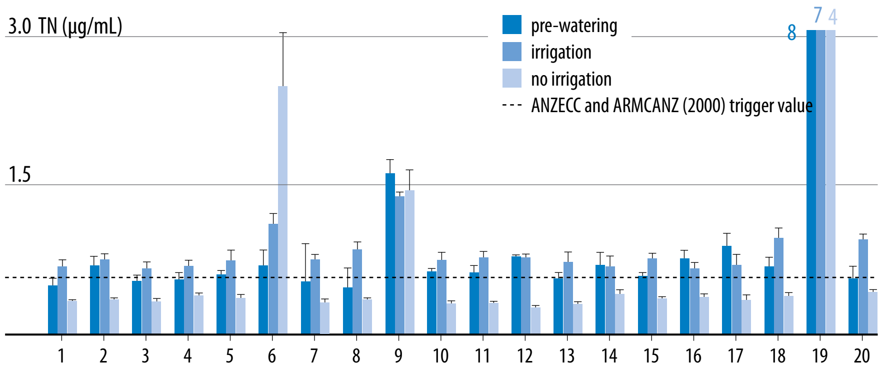
Figure 6.2.7. Salt parameters, upstream (Site 1, Site 2) and downstream (Site 18, Site 20) of the irrigation area: a) total dissolved solids concentration, b) total dissolved solids load, c) chloride concentration, d) chloride load



Nutrients

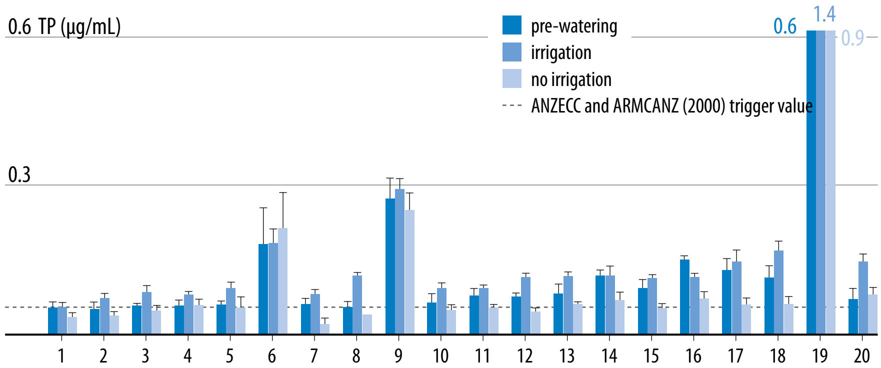
Figure 6.2.8 shows that the Gwydir River and its anabranches are relatively high in nitrogen. Median total nitrogen (TN) level exceeds the ANZECC & ARMCANZ (2000) guidelines for protection of aquatic ecosystems (0.6 µg/mL) at all sites within pre-watering and irrigation flow phases. These flow phases coincide with the time when nitrogenous fertilisers are used within the valley, along with the time when storm events are more likely, resulting in run-off and the possible transport of nitrogen into the river system. TN concentration at Site 6, Site 9 and Site 19 were significantly higher than other sites. Livestock grazing is common around each of these sampling sites, which may contribute to higher TN concentration. All sites except Site 19 meet the ANZECC & ARMCANZ (2000) guidelines for irrigation water (<5 µg/mL).

Figure 6.2.8. Median total nitrogen



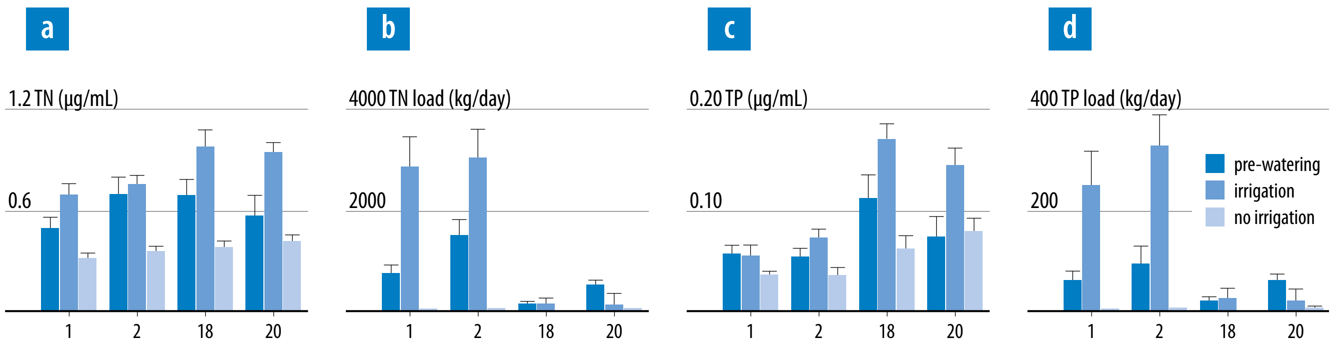
Median total phosphorus (TP) at all sites exceeds the ANZECC & ARMCANZ guidelines for protection of aquatic ecosystems and irrigation waters (0.05 µg/mL), as shown in Figure 6.2.9. Median TP is significantly higher during the pre-watering and irrigation phase for all sites except Site 6, Site 9 and Site 19. As phosphorus has a low solubility, it is rarely dissolved in run-off water, but is carried by suspended silt and clay particles (Mawhinney 1998). Site 9 and Site 19 only flow during flood or local rainfall events that produce run-off, therefore phosphorus would be carried into the river system bound to suspended sediment carried in the run-off water. Site 6 is located in the Gingham watercourse; grazing livestock that cause erosion to streambanks may be one factor causing higher TP levels at this site.

Figure 6.2.9. Median total phosphorus



The concentration of TN and TP is higher at the downstream sites. In contrast, the loads are significantly lower at the downstream sites compared to the upstream sites as shown in Figure 6.2.10. The difference in loads is a direct effect of different flows between the sites.

Figure 6.2.10. Salt parameters, upstream (Site 1,Site 2) and downstream (Site 18,Site 20) of the irrigation area: a) total nitrogen concentration, b) total nitrogen load, c) total phosphorus concentration, d) total phosphorus load.



The median load of TN during the irrigation phase for Site 1 was 2790 kg N/day, whereas a median of only 133 kg N/day flowed past Site 18 and 103 kg N/day flowed past Site 20 in the same year. This is similar to TP where the median daily load of TP was significantly greater at Site 1 with 249 kg P/day flowing past this site, compared with only 23 kg P/day flowing past Site 18 and 18 kg P/day flowing past Site 20 in the same year.

Conclusions

As irrigators are required to retain tailwater and run-off water on-farm, there should be little input of sediment, salts and nutrient from the irrigation industry. During flood events, some water could be released off-farm and make its way into the river system, but as irrigated land amounts to less than 4 per cent of the Gwydir Valley, the amount of water coming off these farms would be a very small proportion of total run-off in a major flood event. It should be noted that, during a flood event, as the water spreads over the vast flood plains, it is impossible to determine the source of the sediments, salts and nutrients.

All sites below Moree exceed the water quality guidelines for turbidity. Turbidity increases along the valley as a reflection of the cumulative effects of land use, streambank erosion and re-suspension of sediments along the valley. River water falls within a low (650 µS/cm –1300 µS/cm) to very low
(<650 µS/cm) salinity class for irrigation water. Although it meets the ANZECC & ARMCANZ (2000) water quality guidelines for irrigation water, it does exceed the guidelines for protection of aquatic ecosystems, although this is largely during the no-irrigation phase.

The median level of total nitrogen and total phosphorus in the river water within the Lower Gwydir Valley exceeds the ANZECC & ARMCANZ (2000) water quality guidelines for protection of aquatic ecosystems. The strategy of recirculating water and containing tailwater and run-off on-farm appears to be preventing higher loads of nutrients, particularly nitrogen, from entering the river system. However, in times of exceptional flooding and inundation some contamination will occur. It is not possible to say that the elevated levels of nutrients in the rivers are a result of irrigation.

Irrigation water sent from Copeton Dam during the pre-watering and irrigation phase has two effects. Firstly, the increased flow rate dilutes the ions in solution, resulting in a lower EC and lower concentrations of nutrients in the irrigation water. Therefore, with regards to the water quality guidelines, the water quality at all sites improves in terms of salinity and nutrients. The second effect of increasing flows is the resulting increase in actual volume of salts and nutrients (that is, load). However, this quantity diminishes down the valley, resulting in much smaller quantities of salt and nutrients leaving the Gwydir Valley and entering the Murray-Darling Basin.

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6.3 Water quality in Queensland catchments and the cotton industry

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Key points

- In the Condamine Balonne Catchment, cotton contributes less than 5% of total nitrogen and phosphorus found in water.
- Total phosphorus levels in the Border Rivers catchment is generally low although it has been increasing over time in some tributaries.
- Total nitrogen levels have been generally below those likely to aid in algal bloom development. In the Condamine Balonne the levels increase with distance downstream from the headwaters – these have been attributed to the high nitrogen content of soils and run-off from upstream land use.
- Studies on cotton farms have shown that total phosphorus and total nitrogen levels increase in tailwater from irrigations.
- Cotton herbicides prometryn and metolachlor increased in detection frequency between 1993 and 2001.
- Atrazine (predominantly used on sorghum) was found in 80-90% of samples over 8 years.
- Since 1999 endosulfan has not been found in water samples in the QMDB.
- Storms and sediment are the two main factors affecting the movement of pesticides and nutrients off-site.
- Mean sediment concentration leaving cotton tail drains ranges from 3 to 9 g/L in storm and irrigation run-off.
- Typical annual soil loss leaving cotton tail drains ranges from 6 to 22 t/ha.
- Median EC values measured at all sites in the QMDB were below 700 µS/cm.
- The high-risk period for off farm movement of pollutants is pre- and post-plant when groundcover levels are below 30%.
- There are a number of practical management options available to farmers now that can dramatically reduce off farm movement of pollutants – for example, planting into stubble and the use of vegetative filters.

Introduction

The quality of surface and groundwater in the Queensland Murray-Darling Basin (QMDB) has significant social, economic and environmental implications for use. This includes its use as a water supply for human consumption, industry and irrigation, and as an ecosystem.

A healthy riverine system is defined as one having the ability to support and maintain a balanced, integrated adaptive community of organisms, and having a species composition diversity and functional organisation which is comparable to that of an undisturbed natural habitat of the region (ANZECC 1992). Catchments require a healthy water system to support human communities, agricultural production and the environment.

The cotton industry, like many industries, impacts on river health through off-site movement of soil, nutrients, insecticides and herbicides into waterways. The impacts of nutrient and pesticide contamination on the aquatic environment and human health have been well documented (Wardrop 1986, Sullivan et al. 1991, AIMS 2002, Chapman 1998). This has increased the level of scrutiny placed on the cotton industry to minimise off-site movement of these pollutants.

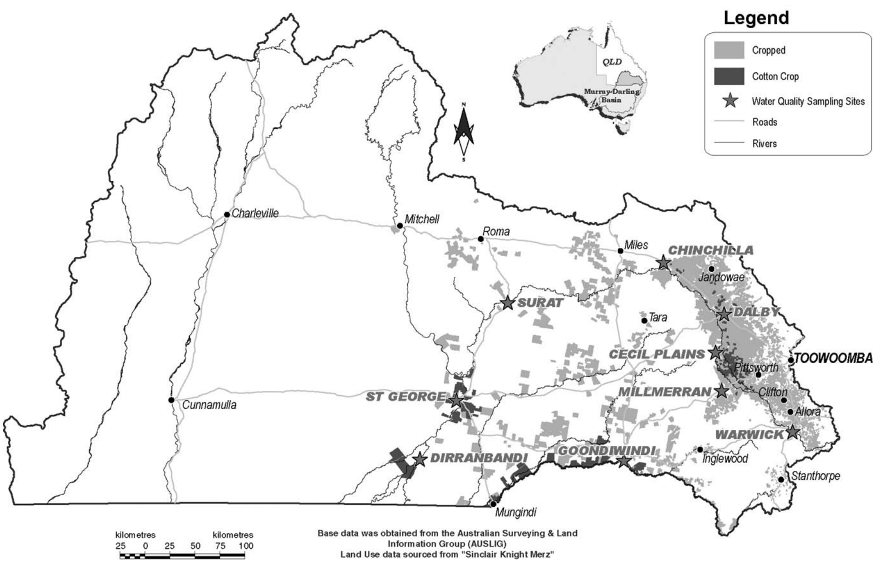
In terms of overall nutrient contribution in the Condamine Balonne Catchment, cotton contributes less than 5% of total nitrogen and phosphorus (CBWC 2001).

The following summary outlines water quality monitoring over the past decade in the QMDB and the key nutrient and pesticide findings over the period.

Water quality in the QMDB

Water quality monitoring in the QMDB has been conducted under two separate programs - one for the Border Rivers and the second for the Condamine Balonne river system (Figure 6.3.1).

Figure 6.3.1. Spatial extent of cotton and cropping areas and water sampling sites on the main river system in the Queensland Murray-Darling Basin



Water quality monitoring for the Border Rivers was conducted as part of the Central North West Region program (Gordon 2001). In 1999-2000 sampling, 29 sites from NSW and Queensland within the region were monitored for nitrogen, phosphorus and 34 agricultural chemicals.

For the Condamine Balonne river system the Condamine Balonne Water Committee Inc. (CBWC) in conjunction with the Qld Department of Natural Resources and Mines (NR&M) established a water quality monitoring program in 1993 which continued through a number of projects until 2002.The major focus of this monitoring was on pesticides.

The NR&M also has an ambient monitoring network looking at total nitrogen (TN) and total phosphorus (TP) for 20 sites dating back 10 years. Total suspended solids (TSS) has been recorded for a more extensive time (up to 30 years at some sites). Of the 20 sites monitored in the Condamine Balonne Catchment, nine are on the main river system.

Pesticides

In 1999-2000 sampling, 29 sites across the region of NSW and Queensland were monitored for 34 agricultural chemicals. Endosulfan, atrazine, diuron, fluometuron, metolachlor and prometryn were detected. Atrazine was the most frequently detected herbicide, with the second most frequently detected chemical being endosulfan.

The CBWC pesticide-monitoring program was conducted at the following town weirs - Millmerran, Cecil Plains, Dalby, Chinchilla, Surat, St George and Dirranbandi in the Condamine Balonne River system. This work was continued in the later years through funding provided by the chemical company Syngenta. Cotton is grown upstream of all sampling locations and would therefore have the potential to contribute to contamination of the water bodies sampled.

Water samples were analysed for 52 pesticides. These chemicals included the alpha and beta isomers of endosulfan, as well as endosulfan sulfate and the breakdown products of atrazine - desethyl atrazine and hydroxy atrazine. Eight chemicals were detected in all five weirs: metolachlor, dieldrin, simazine, atrazine, atrazine desethyl, atrazine desisopropyl, prometryn. A byproduct of DDT (p,p-DDE) was detected on one occasion.

General findings from the study were:

- Metolachlor and atrazine were found in all weirs sampled.
- Metolachlor was found in 60% to 90% of all samples.
- Atrazine was found in 80% to 90% of samples in Dalby, Chinchilla and Surat weirs.

A summary of data from 1993 to 1998 for the two sites with continuous data for the period, Loudoun and Chinchilla Weirs, is given in Table 6.3.1.

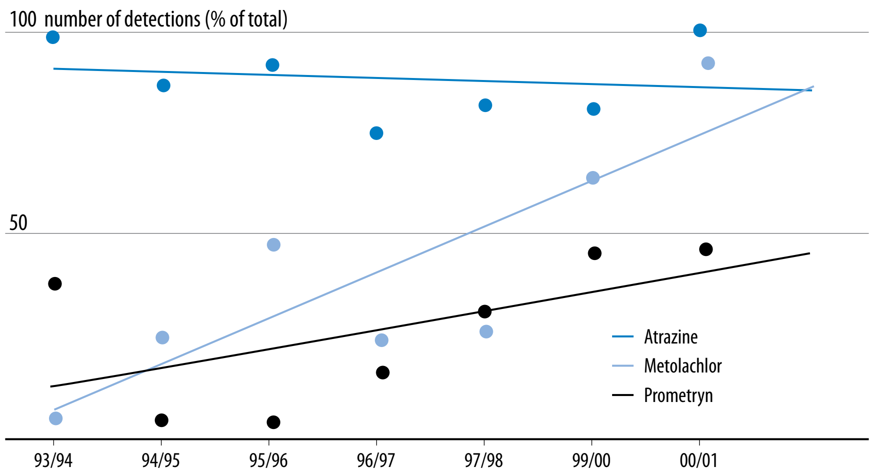
Table 6.3.1. Number of detections of simazine, atrazine, total endosulfan, prometryn & metolachlor for Loudoun & Chinchilla Weir across eight seasons

Chemical	Simazine	Atrazine	Total endosulfan	Prometryn	Metolachlor	Total no. samples analysed
93/94	0	18	12	7	1	18
94/95	0	20	4	1	6	23
95/96	0	21	7	1	11	23
96/97	0	18	6	4	6	24
97/98	0	18	2	7	6	22
98/99	NS	NS	NS	NS	NS	NS
99/00	0	9	0	5	7	11
00/01	5	13	0	6	12	13
01/--*	0	2	0	2	2	4

NS = Not samples *= Incomplete record

The herbicide atrazine, which is predominantly used on sorghum, was the most frequently detected, followed by metolachlor. Detections of atrazine remained constant across all seasons in 80-100% of samples (Figure 6.3.2).

Figure 6.3.2. Metolachlor and Prometryn detections have significantly increased from 1993-2001 with little change in the number of samples containing atrazine for the same period, remaining above 80% for Loudon and Chinchilla Weirs.



The reduction in use of endosulfan by the cotton industry from 1999 has had a dramatic effect on detections in stream. For the past three seasons endosulfan has not been detected in any of the watercourses on the Condamine Balonne river system.

As in northern NSW, herbicides such as prometryn and metolachlor have significantly increased in detection frequency between 1993 and 2001. Both are herbicides used in the cotton industry.

Bed load sediment sampling for pesticides

Sampling of bedload sediments in all town weirs from 1998–99 found traces of endosulfan sulfate (a breakdown product of endosulfan) in three of the forty sediment samples collected. No pesticides were detected in any of the samples collected in February and October 2000.

Endosulfan sulfate was not detected in the sediment on more than one occasion at any site. This finding suggests that the pesticide is leaching back into the water and breaking down and not accumulating in the bedload sediments.

Groundwater sampling for pesticides

Groundwater bores were sampled at Millmerran, Dalby, Chinchilla and St George every 6 months in 1998 and 1999 to determine if there was any leaching of pesticides into the groundwater system (CBWC 2001). No pesticides were detected in any of the monitored bores. An additional bore tested on two occasions in 2001 in a cropping area close to Dalby had traces of a number of chemicals including endosulfan, metolachlor, trifluralin, atrazine, chlorpyrifos and prometryn. This is the first agricultural bore sample in the Condamine Balonne Catchment to show a positive detection to date.

Suspended solids (TSS) and turbidity

In the upper reaches of the Border Rivers Catchment turbidity is generally low (below 20 nephelometric turbidity units - NTUs), however median turbidity values increase to 120 NTU at the lower end of the catchment (McGloin 2001). High turbidity also occurs in some tributaries (for example, 325 NTU in the Weir River). Monitoring over the last 10 to 15 years has shown that turbidity levels have been increasing over time in the lower half of the catchment and in several tributaries (such as the Severn River (Qld), the Macintyre Brook, the Weir River and Oakey Creek).

TSS and turbidity in the Condamine Balonne River System increase with distance downstream, with turbidity levels ranging from 10–100 NTU and TSS 0–0.16 g/L in the uplands to 100–500 NTU and TSS (0.5-1.5 g/L) from Chinchilla to St George (CBWC 1999).

Unlike pesticides, it is difficult to isolate the direct cause of an increase in sediment and turbidity. However, studies by Noble et al. (1997) in the Emerald Irrigation Area found median sediment concentrations measured upstream (0.03 g/L) of the irrigation channel network increased to 1.76 g/L leaving the cotton farm, and reduced to 0.154 g/L downstream of the irrigation channel network. They reported that concentrations found leaving the fields were above those for any river site studied although concentrations leaving the network were comparable to many mid to lower catchment river sites.

Waters et al. (2001) and Carroll et al. (1995) found mean sediment concentration leaving conventional cotton farms ranged from 2.6 to 8.4 g/L in storm and irrigation run-off. Total soil loss for the season ranged from 6 to 22 t/ha.

The highest risk period is early in the season when groundcover is low and high intensity rainfall event occur. Therefore, where storm run-off is not contained, as in some dryland cotton farming systems, management actions such as vegetative filters are highly desirable to minimise their early season risk of increased run-off and sediment loads moving off-farm.

Total phosphorus (TP)

Nutrient enrichment of waterways in run-off from cropping areas can result in the growth of large masses of plant material. ANZECC's 1992 TP guidelines for the prevention of nuisance algal growth use an indicative range of 0.01–0.1 mg/L (milligrams per litre) for freshwater rivers and streams.

In the Border Rivers Catchment TP concentrations are generally low (0.025–0.1 mg/L) (McGloin 2001). Despite this, TP levels have been shown to be increasing over the last 10 to 15 years in several areas including the Macintyre River at Boggabilla, the Dumaresq River at Bonshaw, the Beardy and Severn (Qld) rivers and Tenterfield Creek. The Weir River (a tributary of the Macintyre/Barwon River) has a high median value (0.17 mg/L) but TP levels do not appear to be increasing over time.

In the Condamine Balonne river system, TP levels generally increase with distance downstream (0.1–1.0 mg/L). In general, TP concentrations increase with flow, TSS and turbidity and decrease with electrical conductivity. The association of TP with flow, turbidity and TSS suggests that the major inputs of phosphorus are attached to sediments or organic matter.

Typical levels of TP measured by Waters et al. (2001) leaving cotton farms were 0.97 mg/L. Noble et al. (1996) found in the Emerald Irrigation area that TP loads increased from (0.04 mg/L) upstream of cotton farms to (0.148 mg/L) in irrigation run-off water downstream of the cotton irrigation channel network. Downstream figures were below those measured in adjacent rivers in the basin.

Total nitrogen (TN)

TN guideline values are only indicative with respect to algal bloom development and are only one of a number of other factors influencing algal growth. The recommended range for freshwater rivers and streams, for the prevention of nuisance algal growth is 0.1-0.75 mg/L (ANZECC 1992).

TN concentrations in the Border Rivers Catchment are generally below the upper range for the prevention of nuisance algal growth (0.5-0.75 mg/L) (McGloin 2001). The only site with a median TN value that exceeds guideline values is the Weir River (1.2 mg/L). Nitrogen concentrations have been increasing over the last decade in the Weir River, the upper reaches of the Macintyre River, the lower Dumaresq River, the Macintyre Brook, the Severn (Qld), and the Beardy Rivers.

For the Condamine Balonne, TN concentrations generally increase with distance downstream. TN ranged from 0.1 to 0.9 mg/L in the headwaters and in the lower end of the catchment, while the Maranoa and the Warrego rivers TN ranged from 1.1 to 2.9 mg/L. The high TN observed in the lower end of the catchment can be attributed to the high nitrogen content of the soils and run-off from upstream land use.

Typical levels of TN measured by Waters et al. (2001) leaving cotton farms were 12.38 mg/L and Noble et al. (1996) in the Emerald Irrigation area found that median TN loads measured upstream (0.556 mg/L) and downstream (5.78 mg/L) of a cotton irrigation channel network resulted in an increase in TN in run-off water. Downstream figures were extremely high and suggest that there is a significant contribution of nitrogen in irrigation run-off water.

Electrical conductivity (EC)

EC measures the ability of a solution to carry an electrical current and is dependent on the presence and concentration of inorganic salts including sodium chloride, calcium chloride and magnesium sulfate. Salinity is defined as the total concentration of these ions and electrical conductivity is often used as an alternative measure of salinity (CBWC, 1999).

Surface water throughout the QMDB is generally of low electrical conductivity (less than 300 µS/cm). However, it should be noted that this does not indicate that these waters will not have salinity problems in the future, as salinity problems can take over fifty years to become visible in the landscape.

A number of tributaries in the Border Rivers Catchment have elevated EC levels (300–660 µS/cm) in comparison to all other sites – these include the Macintyre Brook, Oakey and Pike Creek which had medium salinity levels but no significant upward trend. This may indicate that this is a natural state for these tributaries. The Weir River, Pike Creek upstream of Glenlyon Dam and the Severn River (NSW) upstream at Strathbogie, have low EC levels, however these have been increasing since the early 1990s in the Weir and Severn (NSW) rivers and since the late 1950s in Pike Creek.

Median EC values measured at all sites in the QMDC were below 700 µS/cm. Hence water quality at all monitoring locations could be regarded as suitable for irrigation purposes (ANZECC & ARMCANZ 2000).

Minimising off-site movement of pollutants

The cotton industry has invested significant R&D funds over the past decade to address the issue of off-site movement of pollutants. Key findings from the work identified the high-risk period as early season and highlighted the importance of storms and sediment in moving pesticides off-site and the importance of groundcover in reducing movement (Simpson et al. 1996; Silburn et al. 1998).

Waters et al. (2000) demonstrated that there are a number of practical management options available to farmers now that can dramatically reduce off-farm movement of pollutants. Containment of pollutants on farm requires a whole farm approach. Techniques such as sumps, silt traps and vegetative filters are effective in collecting sediment once it has left the paddock. Crop rotations and stubble retention offers the most effective means of reducing 'off-site' movement of sediment bound pollutants for both irrigation and storms at this point in time. Cereal crops have been shown to be the most effective in terms of achieving high cover levels and having minimal impact on soil-borne diseases. To control chemicals which are more water-soluble is a separate issue again.

One technique alone will not address all the problems. An integrated approach which looks at the whole farm design and management is highly effective in reducing the associated risks of off-site movement of pollutants.

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Section 7

Glossary

7.1 Glossary

alluvial: (soil) developed from recently deposited alluvium; usually too young to show the effects of soil forming processes: any layers in the soil profile are successive deposits rather than soil horizons.

bypass flow: the rapid movement of water down macropores ahead of a wetting front. It occurs even though the soil matrix surrounding the macropores is unsaturated (i.e. the water 'bypasses' the soil matrix). The result is that the soil profile is wet from the bottom-up despite the water being applied to the surface. The macropores through which bypass flow occurs include shrinkage cracks, cylindrical pores created by worms or roots and slickensides. It is also called preferential flow.

crop water use index (CWUI) is a measure of lint yield per millimetre of water used by a crop.

cross fall: lateral fall across the field (that is, across the slope of land, as opposed to down the slope of the furrow)

cut-out: when the bolls are consuming all the available energy (carbon) generated through photosynthesis and therefore no new squares are produced.

deep drainage: drainage of water below the root zone.

deficit irrigation: a strategy whereby the total seasonal irrigation water application is less than the irrigation requirements. In such situations, irrigation applications are usually concentrated during those stages of growth that most impact on crop yield. At other times, irrigation may be minimal or non-existent.

deficit (soil moisture): see soil moisture deficit

deficit (regulated deficit irrigation): see regulated deficit irrigation

dynamic deficit: a concept in cotton irrigation scheduling whereby the deficit at which irrigation is triggered changes throughout the season based on forecast ET_0. When forecast ET_0 is high, irrigation is triggered earlier and when forecast ET_0 is low, irrigation may be delayed without influencing yield.

evapotranspiration (ET): the sum of direct evaporation from the soil surface and transpiration, by which process plants give off water vapour through their leaves

exchangeable sodium percentage (ESP): the number of exchangeable sodium ions as a percentage of all exchangeable cations held by a soil. The critical ESP value above which dispersion occurs ranges from 2 to 15, depending on the amount of electrolyte in soil solution.

fetch: the area upwind of a site of interest (e.g. a storage). The characteristics of this area will influence the evaporative potential of the wind.

freeboard: height between bank and water surface in the distribution channel or storage.

gilgai country: a natural surface feature of humps and depressions found in some types of cracking clay

global positioning system (GPS): a network of satellites controlled by the US Department of Defence that is designed to determine a radio receiver's position in latitude, longitude and altitude. Differential GPS (DGPS) improves accuracy of the information via the use of a local base station.

gross production water use index (GPWUI): a performance indicator that compares yield to the total amount of water contributed, including irrigation, rainfall and soil moisture. Rainfall may be either total or effective and should be specified as such. GPWUI can be applied at the field or farm scale.

headworks: main control structure in an irrigation scheme, that is, at the main dam in a catchment.

hydraulic conductivity: the rate of flow of water per unit gradient of hydraulic potential

indeterminate varieties: varieties that have no defined growth period, usually perennial species.

irrigation system efficiency: compares water input to water output (used). Examples include application efficiency (for fields), storage efficiency (for storages) or farm efficiency (for the whole farm).

irrigation water use index (IWUI): a performance indicator that compares yield to the amount of irrigation water contributed. IWUI can be applied at the field or farm scale.

leaching fraction: the fraction of infiltrated irrigation water that percolates below a plant root zone. When using this number, you need to specify the time over which the leaching fraction is measured and the depth interval over which it is calculated.

managed system capacity: the long run maximum rate of water application by an irrigation system, after application efficiency and typical system down time is taken into account. Also see **system capacity**

neutron moisture meter: a radioactive moisture sensor that is lowered down an aluminium access tube. It estimates volumetric soil water content through measurement of neutrons that are scattered by hydrogen atoms in soil water.

nodes above white flower (NAWF): the number of nodes (branches) above the most recent white flower on the first fruiting position. Crops with more nodes above white flower generally have more vigour and this can be used to help decide when crops should be watered.

off-allocation: water flowing down the river which is available to be pumped without being debited to your water account.

partial rootzone drying: the creation of simultaneous wet and dry zones within a crop root zone. The intent is to stimulate plant chemical signals that reduce leaf area and stomatal aperture without decreasing yield.

plant available water capacity (PAWC): the maximum amount of water that a soil can hold in the root zone and later release to plant roots. Water held between 'field capacity' and 'refill point' is referred to as being readily available.

polyacrylamide (PAM): a settling agent used to flocculate soil particles. It is used to in a wide range of applications including reducing sediment transport and erosion (where it also tends to increase soil infiltration), reducing seepage from channels and storages and potentially decreasing evaporation. Care is required as the results of use may be difficult to accurately predict.

porosity: the degree to which a soil is permeated with pores. The term refers not only to the fraction of the soil volume made up of pores, but also to the size and shape of the pores and the degree of connection between them.

pre-irrigation: applying an irrigation some time before planting so that the crop is sown into moist soil. The alternative would be to **water up**.

rilling erosion: an erosion process on sloping land in which numerous and randomly occurring small channels only several centimetres deep are formed.

regolith: the unconsolidated geological material above the base rock which includes the soil profile.

regulated deficit lirrigation (RDI): an irrigation scheduling strategy that involves regulating the soil moisture deficit between predetermined upper and lower limits. The soil moisture deficit range is chosen to prevent significant drought stress and to avoid excessive vegetative growth that may stem from an abundance of water. Precision irrigation systems such as CPLM or drip are usually required to achieve the desired level of control.

saturated hydraulic conductivity (Ksat): the saturated rate of flow of water per unit gradient of hydraulic potential.

Siemens: unit of conductivity.

slaking: collapse of aggregates in water to form microaggregates, due to the breakage of bonds formed, for example, by organic matter.

slickenside: shiny, striated stress surface found on clay-rich aggregates, formed by one mass of soil sliding past another during swelling and shrinking cycles.

slumping: collapse (of a furrow hill).

sodicity: an excess of exchangeable sodium, causing soil dispersion to occur.

soilcore: a sample of soil taken from down the profile.

squares: fruiting structures prior to cotton flowering.

stomate: a leaf pore.

'sub-up': the lateral flow of water from furrows into raised beds or hills.

system capacity: the maximum rate at which irrigation water can be applied by an irrigation system, measured in mm per day. Also **see managed system capacity**.

telemetry: direct transfer of information via radiowaves from the field to computer.

vapour pressure deficit: the differences between the amount of water vapour the air can hold at the current temperature and the amount it does hold. Units are kPa. Vapour pressure deficit is the driving force for evaporation.

vertosols: Australian term used to describe a soil which 'turns' (tills) itself (Latin verto – to turn). Vertosols have more than 35% clay throughout the profile, cracks greater than 5 mm at some time of the year, and the presence of slickensides. Vertosols lack distinct horizons.

water budget: a calculation of current and future water supply and demand, usually calculated for a crop season.

water use efficiency: a generic label for any performance indicators used to study water use in crop production. This includes water use indices (such as IWUI and GPWUI), irrigation system efficiencies and economic indices.

watering up: planting into dry soil and applying a full irrigation immediately after sowing. The alternative would be to **pre-irrigate**.

7.2 Acronyms

Following is a list of acronyms that are used in the cotton industry or by Government, which may appear in this publication.

ABARE – Australian Bureau of Agricultural and Resource Economics

ACCRC – Australian Cotton Cooperative Research Centre (also Cotton CRC)

ACEC – Australian Cotton Exhibition Centre

ACGRA – Australian Cotton Growers' Research Association

ACIC – Australian Cotton Industry Council

ACRI – Australian Cotton Research Institute

ACSA – Australian Cotton Shippers Association

APSRU – Agricultural Production Systems Research Unit

APVMA – Australian Pesticides and Veterinary Medicine Authority (formerly NRA)

AWM – Area Wide Management

BMP – Best Management Practices

Bt – *Bacillus thuringiensis* (crystal protein expressed in INGARD® and BOLLGARD II®)

CA – Cotton Australia

CCA – Crop Consultants Australia

CCCCRC - Cotton Catchment Communities Cooperative Research Centre (also Cotton CRC)

CGA – Cotton Growers' Association

CIE – Centre for International Economics

CRC – Cooperative Research Centre (see CCCCRC)

CRCIF – Cooperative Research Centre for Irrigation Futures

CRDC – Cotton Research and Development Corporation

CSIRO – Commonwealth Scientific and Industrial Research Organisation

DAFF – Department of Agriculture Fisheries and Forestry

DIPNR – Department of Infrastructure, Planning & Natural Resources (NSW)

ICAC – International Cotton Advisory Committee

IP – Intellectual Property

IPM – Integrated Pest Management

L&WA – Land & Water Australia

MDBC – Murray Darling Basin Commission

myBMP - The cotton industry's best management practices program.

NRME – Department of Natural Resources, Mines and Energy (Qld)

NSW DPI – New South Wales Department of Primary Industries

DAFF Queensland – Queensland Department of Agriculture Fisheries and Forestry

RCMAC – Raw Cotton Marketing Advisory Committee

TIMS – Transgenic and Insect Management Strategy committee

TRC – Technology Resource Centre (at the ACRI)

Section 8

Attachments

Appendix 8.1
Theoretical flow rates for siphons: head–discharge charts

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This appendix includes 3 charts of theoretical flow rate (in litres per second) for a given combination of operating head (in mm) and siphon internal diameter (ID, in mm). Each chart has been designed for a particular siphon length, representative of the most common lengths provided by manufacturers. The lengths specified are 3.6 m, 4.0 m and 4.3 m.

All charts have a range of operating heads specified in 20 mm increments up to a maximum of 1 m. The siphon sizes specified represent a selection of those widely used. Imperial siphon sizes are specified according to their internal diameter (ID). Different manufacturers should provide a siphon of similar ID, taking account of manufacturing tolerances.

Metric siphon sizes are specified according to outside diameter (OD) and hence the corresponding ID (which is the figure essential for determining flow) varies according to the variation in pipe wall thickness used for different pipe classes. For this reason, the charts may have more than one value of ID for a corresponding metric OD. It is imperative that siphon ID is measured to determine the appropriate corresponding chart ID. Measure the ID in more than one direction, and average the readings to account for any ovalness.

As can be seen on the charts, even a very small increase in ID (3 mm) can have a dramatic increase in the rate of discharge, particularly as head increases.

Because the level of water in the head ditch may vary and the discharge point of the siphon may not be consistent, it is suggested that head is measured for numerous siphons along the length of the head ditch and over a number of irrigations to see the possible variation.

Discharge is also affected by

- non-circular siphon pipes
- siphon inlet orientation (towards, perpendicular to, or away from the direction of flow in the head ditch)
- trash (blocking the siphons):

and even small factors such as water temperature and quality, and so the chart is only a guide to the actual flow rate.

For more detail on how the charts were constructed, see the discussion of **Theoretical flow** after the charts.

Flow rate in litres/seconds (L/s), siphon Length = 3.6 metres

Operating head (mm)	Nominal siphon size, internal diameter (mm)							
	1 ¼", 31.75	1 ½", 38.1	2", 50.85	50 mm, 44.0	50 mm, 47.0	63 mm, 55.5	63 mm, 59.0	75 mm, 65.1
100	0.55	0.83	1.58	1.15	1.33	1.91	2.19	2.71
120	0.60	0.91	1.73	1.26	1.45	2.10	2.40	2.97
140	0.65	0.98	1.87	1.36	1.57	2.27	2.59	3.21
160	0.70	1.05	2.00	1.45	1.68	2.42	2.77	3.43
180	0.74	1.11	2.12	1.54	1.78	2.57	2.94	3.64
200	0.78	1.17	2.23	1.62	1.88	2.71	3.10	3.84
220	0.82	1.23	2.34	1.70	1.97	2.84	3.25	4.03
240	0.85	1.29	2.45	1.78	2.06	2.97	3.39	4.20
260	0.89	1.34	2.55	1.85	2.14	3.09	3.53	4.38
280	0.92	1.39	2.64	1.92	2.22	3.20	3.66	4.54
300	0.95	1.44	2.74	1.98	2.30	3.32	3.79	4.70
320	0.99	1.49	2.82	2.05	2.37	3.42	3.92	4.86
340	1.02	1.53	2.91	2.11	2.45	3.53	4.04	5.00
360	1.05	1.58	3.00	2.17	2.52	3.63	4.15	5.15
380	1.07	1.62	3.08	2.23	2.59	3.73	4.27	5.29
400	1.10	1.66	3.16	2.29	2.65	3.83	4.38	5.43
420	1.13	1.70	3.24	2.35	2.72	3.92	4.49	5.56
440	1.16	1.74	3.31	2.40	2.78	4.02	4.59	5.69
460	1.18	1.78	3.39	2.46	2.85	4.11	4.70	5.82
480	1.21	1.82	3.46	2.51	2.91	4.19	4.80	5.95
500	1.23	1.86	3.53	2.56	2.97	4.28	4.90	6.07
520	1.26	1.89	3.60	2.61	3.03	4.37	4.99	6.19
540	1.28	1.93	3.67	2.66	3.08	4.45	5.09	6.31
560	1.30	1.97	3.74	2.71	3.14	4.53	5.18	6.42
580	1.33	2.00	3.80	2.76	3.20	4.61	5.27	6.54
600	1.35	2.03	3.87	2.81	3.25	4.69	5.36	6.65
620	1.37	2.07	3.93	2.85	3.30	4.77	5.45	6.76
640	1.39	2.10	3.99	2.90	3.36	4.84	5.54	6.87
660	1.41	2.13	4.06	2.94	3.41	4.92	5.62	6.97
680	1.44	2.17	4.12	2.99	3.46	4.99	5.71	7.08
700	1.46	2.20	4.18	3.03	3.51	5.07	5.79	7.18
720	1.48	2.23	4.24	3.07	3.56	5.14	5.87	7.28
740	1.50	2.26	4.30	3.12	3.61	5.21	5.96	7.38
760	1.52	2.29	4.35	3.16	3.66	5.28	6.04	7.48
780	1.54	2.32	4.41	3.20	3.71	5.35	6.11	7.58
800	1.56	2.35	4.47	3.24	3.75	5.42	6.19	7.68
820	1.58	2.38	4.52	3.28	3.80	5.48	6.27	7.77
840	1.60	2.41	4.58	3.32	3.85	5.55	6.35	7.87
860	1.62	2.44	4.63	3.36	3.89	5.61	6.42	7.96
880	1.63	2.46	4.68	3.40	3.94	5.68	6.49	8.05
900	1.65	2.49	4.74	3.44	3.98	5.74	6.57	8.14
920	1.67	2.52	4.79	3.48	4.02	5.81	6.64	8.23
940	1.69	2.55	4.84	3.51	4.07	5.87	6.71	8.32
960	1.71	2.57	4.89	3.55	4.11	5.93	6.78	8.41
980	1.72	2.60	4.94	3.59	4.15	5.99	6.85	8.50
1000	1.74	2.63	4.99	3.62	4.20	6.05	6.92	8.58

Flow rate in litres/seconds (L/s), siphon Length = 4.0 metres

Operating head (mm)	Nominal siphon size, internal diameter (mm)							
	1 ¼", 31.75	1 ½", 38.1	2", 50.85	50 mm, 44.0	50 mm, 47.0	63 mm, 55.5	63 mm, 59.0	75 mm, 65.1
100	0.54	0.81	1.54	1.12	1.30	1.87	2.14	2.66
120	0.59	0.89	1.69	1.23	1.42	2.05	2.35	2.92
140	0.63	0.96	1.83	1.32	1.53	2.22	2.54	3.15
160	0.68	1.02	1.95	1.41	1.64	2.37	2.71	3.37
180	0.72	1.09	2.07	1.50	1.74	2.51	2.88	3.57
200	0.76	1.14	2.18	1.58	1.83	2.65	3.03	3.76
220	0.79	1.20	2.29	1.66	1.92	2.78	3.18	3.95
240	0.83	1.25	2.39	1.73	2.01	2.90	3.32	4.12
260	0.86	1.30	2.49	1.80	2.09	3.02	3.46	4.29
280	0.90	1.35	2.58	1.87	2.17	3.14	3.59	4.45
300	0.93	1.40	2.67	1.94	2.24	3.25	3.71	4.61
320	0.96	1.45	2.76	2.00	2.32	3.35	3.84	4.76
340	0.99	1.49	2.85	2.06	2.39	3.46	3.95	4.91
360	1.02	1.54	2.93	2.12	2.46	3.56	4.07	5.05
380	1.04	1.58	3.01	2.18	2.53	3.65	4.18	5.19
400	1.07	1.62	3.09	2.24	2.59	3.75	4.29	5.32
420	1.10	1.66	3.16	2.29	2.66	3.84	4.40	5.46
440	1.12	1.70	3.24	2.35	2.72	3.93	4.50	5.58
460	1.15	1.74	3.31	2.40	2.78	4.02	4.60	5.71
480	1.17	1.77	3.38	2.45	2.84	4.11	4.70	5.83
500	1.20	1.81	3.45	2.50	2.90	4.19	4.80	5.95
520	1.22	1.85	3.52	2.55	2.95	4.27	4.89	6.07
540	1.24	1.88	3.59	2.60	3.01	4.36	4.98	6.19
560	1.27	1.91	3.65	2.65	3.07	4.43	5.08	6.30
580	1.29	1.95	3.72	2.69	3.12	4.51	5.17	6.41
600	1.31	1.98	3.78	2.74	3.17	4.59	5.25	6.52
620	1.33	2.01	3.84	2.78	3.23	4.67	5.34	6.63
640	1.35	2.05	3.91	2.83	3.28	4.74	5.43	6.73
660	1.37	2.08	3.97	2.87	3.33	4.81	5.51	6.84
680	1.40	2.11	4.03	2.92	3.38	4.89	5.59	6.94
700	1.42	2.14	4.08	2.96	3.43	4.96	5.67	7.04
720	1.44	2.17	4.14	3.00	3.48	5.03	5.75	7.14
740	1.46	2.20	4.20	3.04	3.53	5.10	5.83	7.24
760	1.48	2.23	4.26	3.08	3.57	5.17	5.91	7.34
780	1.49	2.26	4.31	3.12	3.62	5.23	5.99	7.43
800	1.51	2.29	4.37	3.16	3.67	5.30	6.07	7.53
820	1.53	2.32	4.42	3.20	3.71	5.37	6.14	7.62
840	1.55	2.35	4.47	3.24	3.76	5.43	6.22	7.72
860	1.57	2.37	4.53	3.28	3.80	5.50	6.29	7.81
880	1.59	2.40	4.58	3.32	3.84	5.56	6.36	7.90
900	1.61	2.43	4.63	3.35	3.89	5.62	6.43	7.99
920	1.62	2.45	4.68	3.39	3.93	5.68	6.51	8.07
940	1.64	2.48	4.73	3.43	3.97	5.75	6.58	8.16
960	1.66	2.51	4.78	3.46	4.01	5.81	6.65	8.25
980	1.68	2.53	4.83	3.50	4.06	5.87	6.71	8.33
1000	1.69	2.56	4.88	3.54	4.10	5.93	6.78	8.42

Flow rate in litres/seconds (L/s), siphon Length = 4.3 metres

Operating head (mm)	Nominal siphon size, internal diameter (mm)							
	1 ¼", 31.75	1 ½", 38.1	2", 50.85	50 mm, 44.0	50 mm, 47.0	63 mm, 55.5	63 mm, 59.0	75 mm, 65.1
100	0.52	0.79	1.52	1.10	1.27	1.85	2.11	2.62
120	0.57	0.87	1.66	1.20	1.40	2.02	2.31	2.88
140	0.62	0.94	1.80	1.30	1.51	2.18	2.50	3.11
160	0.66	1.00	1.92	1.39	1.61	2.33	2.67	3.32
180	0.70	1.07	2.04	1.47	1.71	2.48	2.83	3.52
200	0.74	1.12	2.15	1.55	1.80	2.61	2.99	3.71
220	0.78	1.18	2.25	1.63	1.89	2.74	3.13	3.89
240	0.81	1.23	2.35	1.70	1.97	2.86	3.27	4.07
260	0.85	1.28	2.45	1.77	2.05	2.98	3.41	4.23
280	0.88	1.33	2.54	1.84	2.13	3.09	3.54	4.39
300	0.91	1.38	2.63	1.90	2.21	3.20	3.66	4.55
320	0.94	1.42	2.72	1.97	2.28	3.30	3.78	4.70
340	0.97	1.46	2.80	2.03	2.35	3.40	3.90	4.84
360	0.99	1.51	2.88	2.08	2.42	3.50	4.01	4.98
380	1.02	1.55	2.96	2.14	2.48	3.60	4.12	5.12
400	1.05	1.59	3.04	2.20	2.55	3.69	4.23	5.25
420	1.07	1.63	3.11	2.25	2.61	3.78	4.33	5.38
440	1.10	1.67	3.19	2.30	2.67	3.87	4.43	5.51
460	1.12	1.70	3.26	2.36	2.73	3.96	4.53	5.63
480	1.15	1.74	3.33	2.41	2.79	4.04	4.63	5.75
500	1.17	1.78	3.40	2.46	2.85	4.13	4.72	5.87
520	1.20	1.81	3.46	2.51	2.91	4.21	4.82	5.99
540	1.22	1.85	3.53	2.55	2.96	4.29	4.91	6.10
560	1.24	1.88	3.59	2.60	3.01	4.37	5.00	6.21
580	1.26	1.91	3.66	2.65	3.07	4.44	5.09	6.32
600	1.28	1.95	3.72	2.69	3.12	4.52	5.18	6.43
620	1.31	1.98	3.78	2.74	3.17	4.59	5.26	6.54
640	1.33	2.01	3.84	2.78	3.22	4.67	5.35	6.64
660	1.35	2.04	3.90	2.82	3.27	4.74	5.43	6.74
680	1.37	2.07	3.96	2.87	3.32	4.81	5.51	6.84
700	1.39	2.10	4.02	2.91	3.37	4.88	5.59	6.94
720	1.41	2.13	4.08	2.95	3.42	4.95	5.67	7.04
740	1.43	2.16	4.13	2.99	3.47	5.02	5.75	7.14
760	1.45	2.19	4.19	3.03	3.51	5.09	5.83	7.24
780	1.46	2.22	4.24	3.07	3.56	5.15	5.90	7.33
800	1.48	2.25	4.30	3.11	3.60	5.22	5.98	7.42
820	1.50	2.27	4.35	3.15	3.65	5.28	6.05	7.52
840	1.52	2.30	4.40	3.18	3.69	5.35	6.12	7.61
860	1.54	2.33	4.45	3.22	3.74	5.41	6.20	7.70
880	1.56	2.36	4.51	3.26	3.78	5.47	6.27	7.79
900	1.57	2.38	4.56	3.30	3.82	5.54	6.34	7.87
920	1.59	2.41	4.61	3.33	3.86	5.60	6.41	7.96
940	1.61	2.43	4.66	3.37	3.91	5.66	6.48	8.05
960	1.62	2.46	4.71	3.40	3.95	5.72	6.55	8.13
980	1.64	2.49	4.76	3.44	3.99	5.78	6.61	8.22
1000	1.66	2.51	4.80	3.47	4.03	5.84	6.68	8.30

Theoretical flow

The equation used to calculate these charts is that proposed by Bos (1989) specifically for measuring theoretical flow through irrigation siphons. This differs from the more usually encountered equation based on Manning's outlet control, which is theoretically inappropriate (Queensland Water Resources Commission, 1984). Values used for entrance and exit loss coefficient (C) and friction factor (f) are 1.9 and 0.019 respectively. These values were decided upon following procedures outlined by Bos, and after careful analysis of available siphon discharge data.

This equation aims to provide the theoretical flow rate of siphons in the field and hence takes account of many in-field hydraulic issues. The charts do not provide a measure of theoretical flow of siphons operating under laboratory conditions.

Equations used

For those interested in calculating flows for siphon lengths or pipe internal diameters that are not specified in the following tables, the equation used is as follows.

$$Q = \frac{\Pi D^2}{4}\left[\frac{2g\Delta h}{1.9 + \frac{fL}{D}}\right]^{0.5}$$

where:

Q – discharge (m^3/s)

D – siphon internal diameter (m)

g – acceleration due to gravity (9.81 m/s^2)

Δh – operating head (m)

f – friction loss coefficient (0.019 in the charts)

L – siphon length (m)

More information regarding the theory and application of this equation is available in Bos (1989).

For reference

The theoretically incorrect Manning's equation that has been used in the past is as follows:

$$Q = 10^{-5}\sqrt{\frac{124 g \Delta h D^{5}}{0.00015 D + \frac{124 n^2 L}{D^{1/3}}}}$$

This equation, and charts based on this equation, should **not** be used, as they are likely to incorrectly estimate the siphon flow rate.

References

Bos, MG 1989, Discharge measurement structures, 3rd edn, ILRI Publication 20, International Institute for Land Reclamation and Improvement, The Netherlands.

Queensland Water Resources Commission 1984, Farm Water Supplies Design Manual vol. II: Irrigation Systems, 2nd edn, Queensland Water Resources Commission, Brisbane.