Technology and practice for irrigation in vegetables

Evan Christen, Jim Ayars,
John Hornbuckle, Mark Hickey

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Technology and practice for irrigation in vegetables

Authors: Evan Christen[1,2], Jim Ayars[3], John Hornbuckle[1,2], Mark Hickey[4]

[1] CSIRO Land and Water, Griffith, NSW, 2680, Australia;

[2] CRC for Irrigation Futures;

[3] USDA-ARS, 9611 S. Riverbend Ave, Parlier, CA 93648, USA;

[4] NSW DPI, Yanco, NSW, Australia

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CONTENTS

FIGURES

TABLES

FOREWORD

It is important to identify the best irrigation practice that will allow the vegetable industry to develop into the future. This means using systems that allow efficient use of water, labour and other resources whilst producing a quality product.

There is also the expectation and opportunity to use unconventional water sources such as reclaimed water, with the need to then determine how much of each water source can be applied without harmful effects on the crop and soil.

Furthermore, water quality, salinity, suspended solids, ions, trace elements and pathogens may influence the choice of irrigation system. For instance, high suspended solids will create filtration problems when using drip irrigation. For another example, sprinkler irrigation methods that wet plant leaves may cause specific ion toxicity problems, e.g. chloride or sodium, at concentrations lower than those that cause problems with surface irrigation methods.

An appropriately designed and operated irrigation system is crucial to maximise production quantity and quality and irrigation efficiency whilst minimising environmental impacts. There can be no definitive answer, however, as to which type of irrigation system is most suitable for vegetable irrigation, as there are so many variables. This report has endeavoured to broadly assess the three main irrigation systems, furrow, sprinkler and drip, against the key criteria related to irrigation for vegetables. The main areas of assessment for irrigation systems are water quality parameters, likelihood of minimising environmental problems, and appropriateness for efficient and economic crop production.

Although the method of water application is dependent on many site and economic considerations, the most efficient system, with least human and environmental risk, is generally considered to be drip irrigation, and so the bulk of this report focuses upon drip irrigation. Drip irrigation may not always be suitable for a particular agricultural system, however, due to soil physical properties, establishment difficulties, cost considerations and other factors outlined in this report.

Good irrigation scheduling and management methods are important to maximise production whilst minimising environmental impacts. Good drainage is also required to suit the soil, water and environmental conditions of the irrigation scheme.

Potential for improving water use efficiency depends on the degree of understanding of the crop and soil system, the flexibility in management offered by the irrigation system and water supply, and the sensitivity of yield-determining factors in providing an economic response to improvements in water management. The issues are further discussed in the Appendix 'Potential use of the water use efficiency and productivity frameworks is assessing returns for irrigation water in the Australian vegetable industry'.

All these factors are crucial for the success and sustainability of any vegetable irrigation.

SECTION 1 – INTRODUCTION

METHODS OF IRRIGATION

The choice of irrigation method has to consider the site conditions, the irrigation water quality, crops grown, labour availability and cost.

Water quality

The choice of irrigation system will depend upon the importance of each parameter. In horticultural irrigation with wastewater there are also the concerns specific to wastewater, such as the opportunity for foliar injury, pathogens that may affect plants, and pathogens that may affect humans. These latter factors may be of greatest importance.

Crops grown

The crop characteristic is very important in terms of establishment and tolerance of waterlogged or saline conditions. Establishment is of critical concern to annual crops. Many horticultural crops are small-seeded, such as onions and tomatoes, and are difficult to establish under many environmental conditions. In other circumstances, establishment is a less critical concern, for instance where transplants are used or the crop is perennial, such as fruit crops.

Other considerations are the crop tolerance to water stress or waterlogging. For example, lettuce crops are extremely sensitive to water stress, and many horticultural crops, for example tomatoes, are susceptible to root phytophthora, and hence waterlogging should be avoided.

The method of irrigation also often affects crop quality in terms of marketability. Tomatoes are prone to low solids content when grown with drip irrigation compared with furrow irrigation. Onion crops are at risk of downy mildew, which can be exacerbated with sprinkler irrigation, as the foliage is frequently wetted.

Water use efficiency

In general terms, irrigation systems need to have high water use efficiency (WUE) (unit product per unit water applied): high WUE is required by the water cost, and to minimise negative environmental effects.

In many situations, the flexibility in timing and amount of water application may be controlled to a large degree by the irrigation water supply. When proposing irrigating with wastewater, the availability of water, timing and volume, needs to be carefully assessed to ensure that the proposed irrigation system and cropping will be viable.

IRRIGATION AND DRAINAGE

The irrigation system and its management are critically important in managing drainage. Drainage is inextricably linked to the irrigation excess, or that portion of irrigation that passes below the root zone and cannot be used by the crop. This is also known as **deep percolation**. The amount of deep percolation is also related to rainfall, since rainfall and irrigation interact to affect the total deep percolation.

Application rate and pattern

Irrigation systems should be selected so that the operational characteristics of the system are suited to the soils and available water supply. The ideal system would apply the same depth of water over the entire area to be irrigated. In reality, the water is spread non-uniformly across the field. One of the major factors for non-uniformity is the interaction of the irrigation system's operational characteristics with the infiltration characteristics of the soil being irrigated. In general, pressurised systems such as sprinklers and drip irrigation can be managed to provide more uniform application, resulting in better control of deep percolation, than is possible with surface systems.

The application rate of a pressurised system can be controlled so that the infiltration rate of the soil is not exceeded and surface run-off and redistribution are minimised. Because water is distributed uniformly at the same time to all parts of the field by closed conduits prior to application, the total depth of applied water can be effectively controlled with a pressurised system. The infiltration intake opportunity time of pressurised systems is roughly equal for the entire field, while surface systems have greater opportunity times at the head of the field than at the tail end. In sprinkler systems, application uniformity is affected by pressure variations in the system, and wind speed and direction. The pressure variation can be corrected by improved design. Wind effects can be minimised by changing sprinkler spacings and operating when wind velocities are below a threshold value.

Drip systems have a highly non-uniform application pattern on the surface which is smoothed out and becomes quite uniform after water has infiltrated (Wallach 1990). Poor hydraulic design can also lead to poor distribution uniformity in drip systems and ultimately excessive deep percolation losses.

Frequency of application

Another advantage of pressurised systems is the ability to operate the system at high frequency, that is, several times a week to several times a day. With this mode of operation, the total water application can be set equal to estimated crop evapotranspiration between the irrigation intervals. If the soil water content in the root zone had been lowered prior to beginning irrigation, then there should be some soil water storage available to reduce the deep percolation resulting from non-uniformity. When the soil water is fully replenished with less frequent irrigation, the soil profile becomes a storage for a large volume of applied water and the deep percolation potential is increased due to non-uniform application.

Specific considerations for surface systems

Surface irrigation systems, such as furrow and level basin systems, can apply water very uniformly if the system is properly designed and operated (Clemmens and Dedrick 1982). These systems work best on soils which contain large percentages of clay and silt.

Techniques to improve distribution uniformity with furrow irrigation include increased furrow flow rate, reduced run length and cut-back flow.

- Increased flow rates in the furrow decrease the advance time of the furrow stream and thus reduce the difference in opportunity time between the ends of the field contributing to improved uniformity. The furrow advance time should not exceed 25% of the total set time.
- Reducing the furrow run length has the same effect on opportunity time as increasing the furrow flow rate.

- Surface run-off is reduced by reducing the furrow flow rate after the advance is completed, that is, by a cut-back flow.

Further reading

ME Jensen (ed.) 1983, *Design and operation of farm irrigation systems*, ASAE Monograph 3, American Society of Agricultural Engineers, St Joseph, Michigan, pp. 447–500.

SECTION 2 – MATCHING CROPS, SOILS, WATER QUALITY AND IRRIGATION METHODS

There can be no definitive answer as to which type of irrigation system is most suitable for vegetable irrigation as there are so many variables. It is possible to broadly rank the three main irrigation systems against the key criteria related to irrigation for vegetables. The main areas of assessment for irrigation systems are against water quality parameters, likelihood of minimising environmental problems, and appropriateness for efficient and economic crop production. The irrigation systems are broadly assessed against these criteria below.

The potential for using a particular system or risk associated with a system based on the criteria have been described as high (H), medium (M), and low (L).

WATER QUALITY

Salinity

The management of soil salinity will be key to irrigation sustainability, especially if reclaimed or saline water is used. Irrigation systems with better water control (ones that can apply water according to crop requirements and with high uniformity) are inherently better suited to managing salinity. Table 1 refers to the management of soil salinity, but leaf burn with sprinkler irrigation may also be a problem when using saline waters.

Table 1 – Water salinity and irrigation system suitability

	Drip		Sprinkler		Furrow
Salinity	Buried	Surface	Fixed, centre pivot	Traveller	
Low	H	H	H	H	M
Moderate	H	H	M**	M	M
High	M	M	L	L	L

H = highly suitable; M = moderately suitable; L = low level of suitability
*Assuming all soils have reasonable drainage; if drainage is very poor, then drip should be used.
** Leaf burn becomes a problem.

Pathogens and aerosols

Where reclaimed water is used for vegetable production, risk of pathogens contaminating the product is one of the key limitations. The risk of contamination varies according to the crop and irrigation system used. Production and drift of aerosols is also an issue (Table 2).

Table 2 – Pathogens, aerosols and risk of contamination

	Drip		Sprinkler		Furrow
Pathogens	Buried	Surface	Fixed, centre pivot	Traveller	
Ingestion risk	L	M	M	H	M
Contact risk	L	H	H	H	H
Aerosol risk	L	L	H	H	L

H = high risk; M = moderate risk; L = low risk

Generally, under the harvest controls developed for class A to D waters (Human Services and Environment Protection Agency SA 1999), sprinkler and furrow irrigation have the same levels of control. Drip irrigation can be used with reclaimed water classes 1 to 2 levels lower. If buried drip is used, then the risks are further reduced.

Clogging, precipitation and corrosion factors

Depending on the water source, there are varying risks of clogging, precipitation and corrosion affecting the operation and longevity of an irrigation system. Generally furrow irrigation is least susceptible to these problems (Table 3).

Table 3 – Clogging, precipitation and corrosion risk, and irrigation system suitability

	Drip		Sprinkler	Furrow
Water quality factor	Buried	Surface	Fixed, centre pivot	
High suspended solids	L	L	M	H
High potential precipitates	L	L	M	H
High biological activity	L	L	M	H
pH < 6, > 9	L	L	L	M

H = high risk; M = moderate risk; L = low risk

ENVIRONMENTAL MANAGEMENT

All irrigation carries potential risks to the environment. These risks are exacerbated if reclaimed waters are used, due to potentially high levels of salts and nutrients. Apart from soil salinity, dealt with above, the other main factors are surface run-off and deep percolation. The risks of these occurring with different systems are outlined below.

Surface run-off

Surface run-off in irrigated agriculture is caused by applying more irrigation water, either in total volume or by rate of application, than can infiltrate into the soil, and is also due to rainfall. This can be a limiting factor to irrigation in some regions. Systems with good control of application rate and amount and with high uniformity have lower likelihood of run-off. Systems with high application rates, such as travellers, make it difficult to control surface run-off and excess drainage into low areas of the crop. Systems that leave parts of the soil surface dry reduce the risk of run-off due to rainfall (Table 4).

Table 4 – Risk of surface run-off with irrigation system and soil type

	Drip		Sprinkler		Furrow
Soil type	Buried	Surface	Fixed, centre pivot	Traveller	
Sand	L	L	L	M	L
Loam	L	L	M	H	M
Clay	L	L	H	H	H

H = high risk; M = moderate risk; L = low risk

Deep percolation

Deep percolation of irrigation water down past the root zone is the other main loss of water irrigation water. Good irrigation management and scheduling is key to minimising deep percolation, no matter which type of system is used. Deep drainage can be considerably higher with furrow irrigation than when using drip or sprinkler irrigation, mainly due to higher non-uniformity of application than with these systems. The risk of deep percolation on very sandy soils is high with all types of irrigation method. Even with the best irrigation management, rainfall can cause considerable deep percolation, so irrigation is not recommended on sandy soils (Table 5).

Table 5 – Deep percolation risk with irrigation system and soil type

	Drip		Sprinkler		Furrow
Soil type	Buried	Surface	Fixed, centre pivot	Traveller	
Sand	M	M	H	H	H
Loam	L	L	L	H	H
Clay	L	L	L	M	M

H = high risk; M = moderate risk; L = low risk

AGRONOMIC FACTORS

Soil–water properties

For good crop production there needs to be an appropriate match between the soil physical properties controlling water movement and retention and the irrigation system. This affects the amount of water that can be stored in the soil after an irrigation, the depth of wetting, wetting pattern and aeration status. These factors affect the ease of management and agronomic productivity of the land (Table 6).

Table 6 – Soil type and system suitability for crop production

	How suitable is this system on this soil type?				
	Drip		Sprinkler		Furrow
Soil type	Buried	Surface	Fixed, centre pivot	Traveller	
Sand	L	M	H	M	L
Loam	H	H	M	M	H
Clay	M	M	L	L	M

H = highly suitable; M = moderately suitable; L = low level of suitability

Crop establishment

Establishment of crops is a critical task in horticulture; the irrigation system must be able to do this with a high degree of success. Table 6 is suitable for this assessment, except when considering a buried drip system, in which case it is very difficult to achieve good seed germination in any soil type. Travellers are generally unsuited to small-seeded crops because of their tendency to wash the soil along seed rows. Table 7 outlines irrigation system suitability for establishing various categories of plant material.

Table 7– System suitability for crop establishment

	Drip		Sprinkler		Furrow
Type of crop	Buried	Surface	Fixed, centre pivot	Traveller	
Small seeded crops	L	M	H	L	M
Large seeded crops	L	H	H	M	H
Transplants or cuttings	H	H	M	M	M

H = highly suitable; M = moderately suitable; L = low level of suitability

Disease

Control of leaf and root diseases, especially fungal diseases, is affected by the irrigation system, crop and soil type. In general, sprinkler systems increase risk of leaf fungal and bacterial infections, whereas furrow irrigation increases the risks of root rots due to waterlogging. Broad assessments of irrigation systems and potential for disease are given below (Table 8).

Table 8 – Irrigation system and disease risk

	Drip		Sprinkler		Furrow
Crop type	Buried	Surface	Fixed, centre pivot	Traveller	
Large surface area crops	L	H	H	M	M
Root crops	L	M	M	M	M
Cucurbits, tomatoes etc	L	H	H	H	M
Trees, vines, cane, fruit	L	H	M	M	M

H = high risk; M = moderate risk; L = low risk

Dust control and cooling

Control of dust is important for some vegetable production, to keep the crop clean. It is also important that the harvested product is dust-free. It may also be important to prevent soil or sand from blowing and so damaging very young and tender plants. In the same category is the task of cooling, which is required for some crops. Sprinkler irrigation provides the best potential for controlling these factors as it wets the entire surface area. A broad assessment of irrigation system potential for these factors is given below (Table 9).

Table 9 – Irrigation system and dust control/cooling

	Control level				
	Drip		Sprinkler		Furrow
Control factor	Buried	Surface	Fixed, centre pivot	Traveller	
Soil/sand blowing	L	L	H	H	M
Dust control	L	L	H	H	M
Cooling	L	L	H	H	M

H = highly suitable; M = moderately suitable; L = low level of suitability

Weed control

Effective weed management is important. With vegetable production, minimal competition is a high priority, and the weed control that can be achieved by different systems is important. Drip systems offer the best potential, as they wet little of the soil. Buried drip systems are even better, as they can be managed so as not to wet the soil surface. Drip in combination with plastic polythene mulch or the use of transplants can be particularly effective for controlling weeds.

It is important to note that certain pre-emergent vegetable herbicides require 'fixing' into the soil with 10–15 mm of overhead irrigation to be most effective. This could preclude the use of drip if alternative herbicides cannot be used.

A broad assessment of irrigation system potential for these factors is given below (Table 10).

Table 10 – Irrigation system and weed control

	Control level				
	Drip*		Sprinkler		Furrow
Weed control	Buried	Surface	Fixed, centre pivot	Traveller	
At germination	H	H	L	L	L
Mid – late season	H	H	L	L	M

*If using pre-emergent herbicides that require watering in, drip irrigation is generally unsuitable.

SUMMARY

This section has described in generalised terms the suitability and risks associated with different systems. The key messages are that irrigation systems with better water control (drip/sprinkler) are more likely to be sustainable and reduce the risks of negative environmental impacts, and that for pathogen control, especially with edible crops, favours the use of drip irrigation and ultimately buried drip irrigation. Drip irrigation although attractive from these points of view has difficulties if there are high suspended solids in the water and if there is a requirement to germinate seeds. Sprinkler irrigation is very useful if dust/soil control and cooling are required.

In the following sections, sprinkler irrigation will be briefly described. The remaining part of this document will discuss in detail the design and management of drip irrigation systems, as these are seen as having the greatest potential for the vegetable industry.

SECTION 3 – SPRINKLER IRRIGATION

Sprinkler irrigation is commonly used in horticultural irrigation. There is a large range of equipment which allows the application rate to be matched to the soil infiltration rate. This is advantageous in that irrigation of sandy soils can occur where furrow irrigation would be unsuitable. However, soils with very low intake rates, less than 3 mm/hour final intake rate, are prone to run-off and need special measures to increase intake or provide uniform surface ponding to prevent run-off (Burt et al. 1999).

Sprinkler irrigation is also suitable for irrigating undulating or steep terrain, although surface run-off can then become a problem. Sprinkler irrigation has the advantage of providing good germination and crop establishment, since small amounts of water can be applied frequently and uniformly, and with many systems the labour requirement for this is low. Sprinkler irrigation also has other agronomic advantages such as control of wind erosion and incorporation or activation of herbicides.

Sprinkler irrigation has its drawbacks: high capital investment and operating costs; foliar application of water, which can raise concerns with specific ion injury; health risks associated with human consumption following foliar contamination; and increased risk of fungal disease. Design and management difficulties with sprinkler irrigation usually occur in two forms: **excessive ponding and run-off** due to a mismatch in application rate and soil infiltration (more often a problem with travelling sprinkler systems because of their extremely high instantaneous application rate); and **excessive deep percolation** (usually due to poor irrigation scheduling and poor distribution uniformity). These problems can be overcome by undertaking adequate soil investigations beforehand and arriving at an appropriate system selection, design, proper system maintenance and good irrigation scheduling techniques.

DISTRIBUTION UNIFORMITY

With sprinkler systems the uniformity of water application depends upon the sprinkler type, its spacing in the row and spacing between rows. The depth of water applied is usually greater near the sprinkler and decreases with distance from the sprinkler. Uniformity of application is achieved by placement of sprinklers such that the wetting patterns overlap, usually about 60–80%. In irrigation design, the engineer considers the nozzle pressure, discharge rate, wetted diameter and water distribution pattern to obtain acceptable uniformity.

Poor distribution uniformity will occur around edges of fields or in odd-shaped fields where sprinkler overlap cannot be maintained.

Each line of sprinklers is considered an individual source, and so the spacing along the line is critical, and not the row-to-row spacing.

Other causes of non-uniformity are pressure drop along the sprinkler line, incorrect system pressures and wind effects. System pressures higher than recommended will cause the water to break up into finer drops, causing more water to fall near the sprinkler, and increasing susceptibility to wind drift and evaporative losses. System pressures lower than recommended will reduce the amount of overlap and will also result in larger water droplets with greater energy and hence a greater application of water at the periphery of the wetting pattern.

TYPES OF SPRINKLER SYSTEMS

Sprinkler systems for field crops include fixed (solid set), hand move (single lines of sprinklers that are moved across the field) and travelling irrigators. A **solid set system** is a system with main line and laterals that remain in place throughout the growing season, well-suited to irrigating crops that need light frequent irrigations. These systems have high capital cost but require very little labour for irrigation. The fixed pipes and risers are obstacles to farming operations. The **hand move system** generally consists of a portable main line that is in place for the growing season and one or two laterals. The laterals are moved right across the field for each irrigation cycle. This system reduces the capital cost but dramatically increases labour costs. These systems should be designed so the average application rate is less than the soil infiltration rate to avoid run-off.

Travelling irrigators include travelling booms and guns, centre pivots and linear moves. Travelling boom and guns are high volume, high pressure systems where the application rate is determined by the sprinkler design, water pressure and advance speed. Because of large droplet size and high application rates these systems are best suited to light soils having high infiltration rates and crops that can sustain heavy wetting and have good groundcover, e.g. pastures, sugar cane. These systems generally have poor uniformity of application (Burt et al. 1999).

Centre pivot and linear move systems carry a row of sprinklers either around in a circle (centre pivot) or across a rectangle of land (linear move). With centre pivot systems the outer end travels much faster than at the circle centre and so instantaneous water application rates are much higher at the end. With both these systems the instantaneous application rate can be 60–250 mm/hour (Heerman and Kohl 1981). This is much higher than the infiltration rate of most soils (Figure 1). Potential run-off risk is decreased by having more frequent smaller irrigations or increasing the wetted footprint. With both these systems there has been a trend towards using nozzles on droppers, so that they are close to soil surface, and run at lower pressure with smaller droplet sizes (Burt et al. 1999). This reduces the application rate and preserves soil structure. These systems used on flat ground can pond water into furrows without run-off. Using these systems also minimises evaporation and negates the impact of wind.

IRRIGATION SCHEDULING

With solid set systems irrigation scheduling is very simple as the whole area can be irrigated to any application depth, and thus light or heavy irrigations can be used in accordance with crop requirements.

Hand move systems are less flexible, since, to reduce labour, irrigation frequency is reduced, resulting in long irrigation times in the range of 8 to 24 hours. The soil moisture deficit is set according to the minimum set time required for labour organisation.

Figure 1 – Lateral move irrigator with application rate exceeding soil infiltration capacity leading to surface ponding and run-off

Source: CSIRO Land and Water

Centre pivots and linear moves have fixed application rate but variable advance speed (i.e. set time). They need a minimum time to complete a cycle across the field, so scheduling needs to balance the days or weeks needed to complete the cycle and apply the desired depth. With these systems it is important not to fall behind in peak demand period, as it is impossible to rapidly apply a large volume of water.

The lateral move system is particularly difficult as it traditionally finishes its cycle at the wet end of the field and has to traverse the full length of the field again prior to starting the next cycle. Non-uniform watering can be employed to overcome this drawback somewhat: this procedure applies a decreasing amount of water as the irrigator crosses the paddock, applying less and less water towards the end of the paddock. This is in anticipation of the next irrigation application occurring earlier at the finishing end than the starting end of the paddock when the irrigator returns.

Further reading

Burt, CM, Clemmens, AJ, Bleisner, R, Merriam, JL and Hardy 1999, *Selection of irrigation methods for agriculture: committee report,* On-farm Irrigation Committee, Water Resources Division, American Society of Civil Engineers, Reston, Virginia.

SECTION 4 – DRIP IRRIGATION

Drip irrigation is likely to be the most suitable form of irrigation for use with effluent water for two important reasons: it limits contact of the effluent water with plants and workers in the fields and it provides the best control over the irrigation water if well managed. The high level of control is important as it leads to high yield of vegetable crops, e.g. 20–30 t/ML for processing tomatoes, compared to 10–20 t/ML for furrow-irrigated crops (Hickey et al. 2001), and it leads to reduced environmental impacts, i.e. no irrigation run-off, minimal rainfall run-off, negligible drainage past the root zone (if managed well), and no wind drift or aerosol-related problems.

INTRODUCTION

Drip is a technologically advanced method of irrigation that can apply accurately metered quantities of water evenly to plants right across a paddock. To achieve this, the water is pumped around the paddock in pipes to emission points that are at the plant root zone. The system is capital intensive, the piping, pump and associated hardware costing upwards of $3000/ha. It is this combination of technology and high capital cost that makes drip irrigation a potentially risky investment. In order for a drip irrigation scheme to be successful it must be well designed, properly installed and well managed.

Drip irrigation of row crops is gradually increasing as the key components for success are converging:

- Systems are designed to a high standard, specifically for Australian farming conditions .
- Cost/ha is declining as more equipment is made in Australia and costs worldwide have become more competitive.
- Skills of irrigation managers are increasing and farm business plans are well developed to ensure sound returns on investment.

Drip irrigation requires high levels of management skill and financial investment and thus is best considered when the chosen crops have already been successfully grown with furrow irrigation, and agronomy, marketing and financial skills are already well developed.

This section outlines the key design and management factors that combine to create a successful drip irrigation enterprise. The topic area is extensive: the main texts used to develop this section were three Californian books and a general text on Australian vegetable growing. (The choice of Californian texts is due to the lack of comprehensive Australian texts.) See further reading.

Further reading

Drip irrigation for row crops (1997), B Hanson, L Schwankl, S Grattan and T Pritchard, Water Management Series publication no. 93-05, University of California Davis, Davis, California.

This book is 230 pages and is very practical covering both design and management in a straightforward manner

Drip and microirrigation for trees, vines and row crops (with special sections on buried drip) (1994), CM Burt and S Styles, The Irrigation Training and Research Center, California Polytechnic State University, San Luis Obispo California.

This book is 255 pages and is extremely comprehensive. Design aspects are covered in detail and management aspects are thoroughly dealt with including many useful practical examples. Management and design guidelines are developed from field experience over many years.

Fertigation (1995), C Burt, K O'Conner, and T Ruehr, The Irrigation Training and Research Center, California Polytechnic State University, San Luis Obispo California.

This comprehensive (295 pages) text deals in detail with equipment, fertiliser chemistry, nutrient processes, plant and soil testing, system maintenance, use of herbicides, insecticides and fungicides and grower experiences.

The principles of drip irrigation

The principle that 'Irrigation can be closely matched to the crop water use on a daily basis' is the overriding principle of drip irrigation and sets it apart from all other irrigation systems. The following are the characteristics of drip systems that allow for this.

- Water is applied frequently at low application rates. Drip irrigation can only apply water at low rates such as 14 mm/day. This means that drip systems are operated frequently and are run for long sets. These features could be considered a constraint to irrigation in a traditional sense in that large soil water deficits cannot be replaced quickly. However, proper management of drip systems to prevent large soil water deficits from occurring creates a root environment where plant water uptake can be near potential rates.
- Water is applied uniformly to all plants. The ability to apply practically the same amount of water to each plant in a paddock is a unique feature of drip irrigation.
- Water is applied directly to the plant root zone. With drip irrigation only the root zone of the plant should be wetted. Thus in the horizontal plane for row crops only the hill or bed is wetted, not the furrow area, and in the vertical plane the water is kept in the root zone by not allowing drainage below it. Thus, in most cases, up to 25% of the paddock area is kept dry.

When the above principles are considered it is not surprising that world record crops of tomatoes have been grown with drip irrigation and large yield increases are often found when drip-irrigated crops are compared to furrow irrigation.

Drip irrigation is particularly difficult to manage. In some cases, yields under drip-irrigated crops are the same as or even less than comparable furrow irrigated crops. This can be due to poor system design or poor system management. It will necessarily take a few seasons of experience to learn the best management for any new irrigation system.

Advantages and disadvantages of drip irrigation

As with any irrigation system, drip offers advantages and disadvantages. With a well-designed and managed system the potential advantages are large and the disadvantages can be minimised.

Drip irrigation will not be suitable in all circumstances. It may not fit in with the current farming system or the potential advantages may not be great enough to cover the costs.

Advantages

- **Improved plant production** – This may be in terms of total yield, quality or both. With a drip system, irrigation takes place frequently (daily at peak ET requirements), allowing the rootzone soil moisture content to be kept at an optimal level. The water stress → aeration stress → water stress cycles found with furrow irrigations are avoided. Christen et al. (1995) measured a 84% reduction in waterlogging from furrow to drip irrigation for tomatoes in the Murrumbidgee Irrigation Area. Drip irrigation allows an optimal soil water status to be maintained across whole paddocks due to the uniform delivery of water to the plants. Uniform application is very difficult to achieve with furrow irrigation and thus some plants are over-watered and others under-watered.
- **Increased irrigation efficiency** – Drip irrigation systems have the potential to deliver high levels of irrigation efficiency. Whether the potential is realised depends upon management skills. Other irrigation systems can achieve comparable levels of irrigation efficiency to drip, but this requires large time commitments from the irrigation manager. Computer-controlled automation also helps to minimise human error in scheduling drip irrigation.

Drip irrigation allows for improved irrigation efficiency by:

- reducing evaporation from the soil surface, since only a small area of the paddock surface is wetted (or none at all if the drip is buried)
- elimination of irrigation run-off. Rainfall run-off should be much reduced as it can be stored in the dry soil between the drip lines.
- reduced water passing below the root zone (deep percolation). Christen et al. (1995) found that only 2% of rainfall drained from below some drip-irrigated tomatoes in the Murrumbidgee Irrigation Area, compared with about 26% of rainfall with furrow irrigation.
- eliminating the tendency to over-irrigate the top end of the paddock to apply sufficient water at the bottom end, as occurs with furrow.

This improved irrigation efficiency is unlikely to result in a reduced paddock water use, as a more vigorous crop with higher yield should be achieved, resulting in increased yield per megalitre (tonnes/ML of saleable portion), as shown in Table 11 and 12.

Table 11 – Drip and furrow irrigation for vegetable crops

	Yield (t/ha)		Water applied (mm)		Productivity (t/ML)	
Crop	Drip	Furrow	Drip	Furrow	Drip	Furrow
Lettuce (1991)	46	49	100	250	47	20
Lettuce (1992)	45	45	225	325	20	14
Tomato (Variety 1)	119	113	675	950	18	12
Tomato (Variety 2)	104	104	675	950	15	11

Source: after Hanson et al. 1997

Table 12 – Tomato yields with drip and furrow irrigation

Irrigation method	Yield (t/ha)	Water applied (mm)
Drip	139	612
Furrow	102	1092

Source: Hermus 1986

McPharlin, Aylmore and Jeffery (1995) showed in Western Australia that drip irrigation can also have advantage over sprinkler irrigation for lettuce production on a sandy soil. With seed-sown lettuce, drip-irrigated lettuce had 19% greater marketable yield, and with transplants there was a 12% yield increase with drip. The economic analysis revealed that the drip irrigation had increased the crop profitability by 21–42%. Germination uniformity, however, can be a problem with buried drip.

Muirhead (1979) showed at Griffith in the MIA that yields of snap beans could be markedly increased using drip irrigation compared to furrow, mainly by avoiding water stress at flowering, with the added benefit of being able to harvest 4 days earlier.

Warriner and Henderson (1989) in an experiment comparing drip and sprinkler irrigated rockmelons at Loxton, SA found that the total yields were the same. However, the marketable yields with drip irrigation were 15–28 % higher than with sprinkler irrigation. This was due to less cracked, blemished or undersized fruit. Also harvest commenced 10 days earlier with the drip irrigation.

- **Improved chemical application** – With drip systems, fertilisers and other chemicals are applied with the water through the system resulting in several advantages over conventional fertiliser application methods:
  - Fertilisers are applied only to the plant root zone.
  - Fertilisers can be applied little and often to more closely match crop nutritional needs.
  - Since run-off and deep percolation are minimised, fertiliser loss is reduced.

Again McPharlin, Aylmore and Jeffery (1995) demonstrated the advantage of drip over sprinkler irrigation by showing that the agronomic nitrogen use efficiency with drip was 25% higher than with sprinkler. This was attributed to better placement and less leaching of the fertiliser.

- **Reduced weed growth** – As only part of the paddock is wetted, and with buried drip the entire surface should be dry, weed growth is reduced. In the wetted areas of surface drip systems, the weed problem may be increased.
- **Reduced disease** – As drip irrigation maintains a dry soil surface, leaf and fruit diseases are often reduced. As the crop root zone is maintained at optimal soil moisture levels, root disease is also often reduced.
- **Irrigation of sloping ground and low water-holding capacity soils** – Since run-off can be minimised with well-designed drip, sloping ground can be used that would be unsuitable for furrow or sprinkler irrigation. Also, undulating ground can be successfully irrigated where landforming costs for furrow irrigation would be prohibitive. As drip irrigation applies small amounts of water frequently it allows successful irrigation of low water-holding capacity soils which would be economically impossible with furrow.

Disadvantages

- **Restricted root zone** – As the drip system only wets a portion of the paddock soil, the crop root zone is restricted to that wetted portion, unless significant rainfall occurs. This results in low total available soil water, and thus the requirement for small, frequent irrigations. The system manager must always remember that the soil water reserves are limited and the capacity for a drip system to 'catch up' are limited. Missed irrigations or breakdowns during the peak demand period are more critical with drip and must be quickly repaired.
- **High maintenance requirements** – Drip irrigation relies upon small diameter passageways in the emitters to control the amount of water being applied. This makes the emitters susceptible to blockage by fine particles, roots and chemical deposits. A filtration system is required to keep particulates out of the system and chemical injection is necessary to prevent chemical deposits, growth of slimes and root growth in the emitters. Preventing blockages is an ongoing task that requires planning and labour. The drip system is also highly susceptible to damage from machinery, chippers, insects and animals. Thus the system needs to be constantly checked, which is difficult with buried systems.
- **Restricted tillage** – If a drip system is to be left in the paddock for several years, then normal tillage operations have to be revised. If the drip tape is laid on the surface it may be retrieved to allow for tillage and then re-laid. The labour costs in retrieval and relaying and the large amounts of damage that can occur to the tape make this an unattractive option. Buried drip tape can be left permanently in the ground for many years, but the depth of tillage is restricted. Remote guidance (GPS) systems have improved tillage management of semi-permanent drip beds and improved precision of placement for both drip tape and tillage implements.
- **Soil structural decline** – With buried drip, an area around the tape remains very wet for long periods of time, and there is the associated risk of soil structural decline. This has been experienced by growers and measured in a field trial in northern Victoria. In this trial, Adem, Aumann and Stirzaker (1996) showed higher soil bulk densities and penetrometer resistance with buried drip irrigation on a duplex soil. The extent or severity of these phenomena is unknown. On a grey self-mulching clay in the MIA, Christen, Moll and Muirhead (1995) found a yield response to gypsum with and without soil loosening in drip-irrigated tomatoes. This was probably due to improved water movement with the gypsum treatments. Gypsum was also found to improve drip-irrigated tomato yields in an alluvial soil in Western Australia (Muller 1993). This experiment found no benefit from deep ripping without gypsum. Design and

management should consider the risk of structural decline. Possible remedies would be growing cereals to dry and loosen the soil, applying gypsum through the drip system and careful tillage. Barber, Katuputiya & Hickey (2000) also found evidence that fine soil particles created a 'choke' immediately surrounding subsurface drippers on medium clay soils after four years of continuous use, resulting in a depleted wetted perimeter.

- **High cost** – Drip irrigation systems are costly, although the cost/ha is declining with better design. The financial aspects of costs and benefits must be carefully considered before a drip system is selected.
- **Difficult crop germination** – Since drip tape is normally buried, the soil needs to be wetted upwards from the tape to the seed line. In many soils this is difficult to achieve and results in complete saturation of the soil. This keeps the soil cold, increases the risk of disease and causes soil structural deterioration.
- **Salt accumulation near the root zone** – Drip systems move salt to the edge of the wetted zone where it accumulates. Leaching by rainfall is required, although leaching using surface drip systems may be possible. Rainfall may leach salt back into the root zone, and drip is often run during rain to force salt below the root zone.

Drip irrigation uniformity

One of the key benefits of drip irrigation is high water application uniformity. If every plant in the paddock were to receive exactly the same amount of water then the system uniformity would be 100%. No irrigation system, not even drip, can actually achieve this: some plants will always get more than others. With drip irrigation the application uniformity depends upon the variation in emitter flow rates throughout the paddock.

The more variation in emitter flow rates, the lower the uniformity. Differences in emitter flow rates are caused by:

- physical variations in each emitter from manufacturing. The degree that one emitter varies from another is called the coefficient of manufacturing variation, *CV*.
- pressure variation within the system, caused by friction in the pipes and fittings and differences in elevation. The degree of variation depends upon the initial design and then how well the system is operated and maintained.
- flow rate variations. For most drip emitters, as the water pressure increases, so too does the flow rate. The relative sensitivity of the emitter flow rate to pressure differences is called the emitter exponent or x. Different emitter types and manufacturers have different exponents.
- emitter clogging. Clogging is often the main cause of variation in drip systems, and can quickly reduce a system designed with a high uniformity to one with a very poor uniformity.

Distribution uniformity

The importance of uniform water application with a drip irrigation system cannot be overstated. With a drip system it is not possible physically to apply large amounts of water across a paddock as occurs with furrow irrigation. Thus, if some plants are not receiving adequate water, there is no way of rectifying the problem with a large 'top-up' irrigation. The benefits of drip irrigation are largely lost if the system has poor uniformity as it will not be possible to achieve optimal water management over the whole paddock, with some areas being too dry, and some too wet. If this is the case then the economic benefits of yield and quality will also be lost and the whole enterprise could be uneconomic.

The uniformity of a drip system is characterised by its *distribution uniformity (DU)*, also known as *emission uniformity (EU)*. The DU is calculated by dividing the minimum emitter flow rate or average of the lowest 25% of emitters by the average flow rate of all the emitters (Burt and Styles 1994). The total DU is a combination of the emission variation due to uneven pressure distribution throughout the paddock and the variation due to the manufacturing variation. Practically, paddock design DU should be >90%.

DESIGN OF A DRIP IRRIGATION SYSTEM FOR ROW CROPS

The design of a drip irrigation system must consider the physical paddock conditions, cropping pattern, management factors, general farming system and cost.

Components

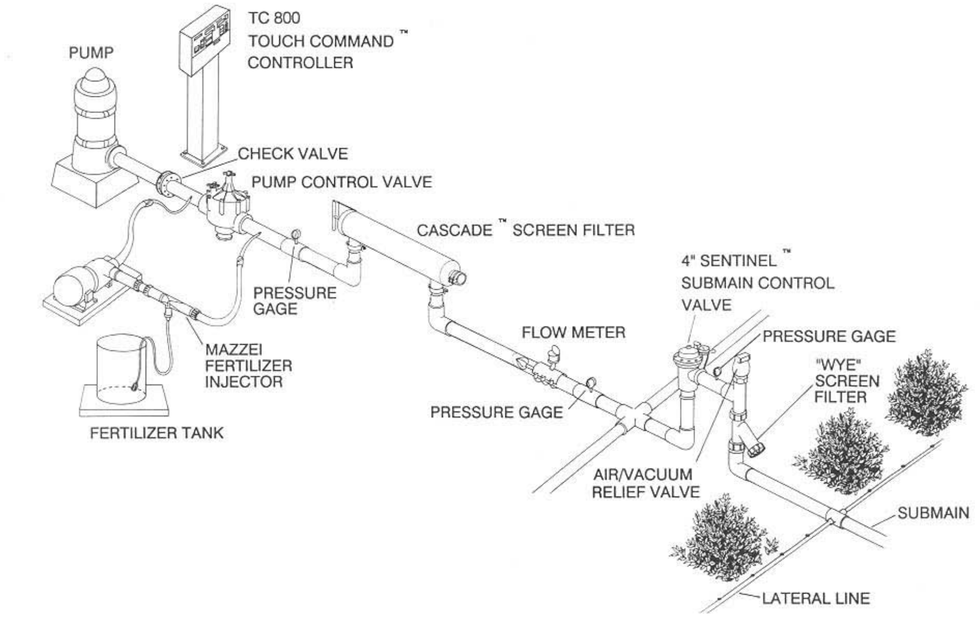
Drip systems have these basic components, typically arranged as shown in Figure 2:

- pump
- filter
- fertiliser injector
- flowmeter
- main lines into submains into manifolds
- drip tape lateral lines from the submains
- valves.

The design needs to consider:

- paddock conditions – soil, slope, shape
- water supply – quality, availability (how much and how often)
- crop – water requirements, rooting pattern

Figure 2 – Drip irrigation system layout



Source Boswell 1990

- management – skill, level of automation
- lifetime – permanent or temporary/portable system
- farming system – tillage requirements, farm layout
- economics – system cost is traded off against DU, ease of management, clogging vulnerability, durability and risk minimisation.

Wall thickness

In row crops thin walled pipe is usually used for the laterals. The wall of this pipe is so thin (0.1 to 0.6 mm) that the tube lies flat. This is termed drip 'tape' as opposed to 'hard wall', which is much thicker pipe that keeps a circular shape. With buried drip a thicker tape is used. This is more expensive, but is less easily damaged and can withstand higher pressures. Hard wall tape is extremely durable and can be retrieved from the paddock much more effectively than tape.

Tape diameter

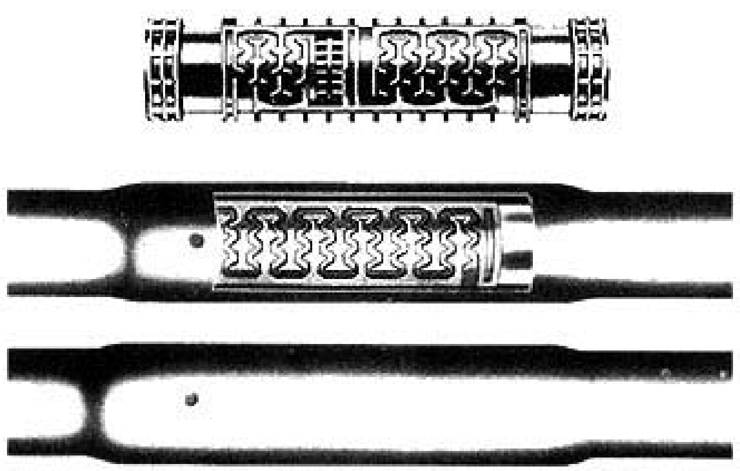
Drip tape comes in many sizes. Larger diameter tape is more expensive but has the advantage of reduced friction losses, allowing longer runs.

Emitter type

Most emitters are the turbulent flow type, that is the flow path creates turbulence in the water, this allows for larger flow passages which are less likely to become clogged, Figure 3. Emitters can be fairly short and welded on the inside of the tape, or can be quite long and part of the tape seam. In-line emitters are used with hard wall pipe and are actually part of the pipe.

Pressure compensating emitters have diaphragms or flexible orifices that adjust with the water pressure to maintain a constant flow rate. These emitters are useful where very long lateral runs are required or there are large elevation changes. Pressure compensating emitters are variable in their effectiveness in maintaining a constant flow rate and only operate within a certain range. Disadvantages with pressure compensating emitters are that particulates may become lodged holding the diaphragm open and thus allowing too much water to discharge.

Figure 3 – Sections through a drip irrigation emitter



Source: Wang Co. Ltd, http://www.wangco.co.kr/image/drip-pic.gif

Hydraulic parameters

When selecting drip tape, the main considerations are the desired water application rate, emitter spacing, clogging susceptibility and distribution uniformity. Some tapes discharge water more uniformly than others.

Application rate

The desired water application rate is calculated in the section on 'Determining the system flow rate' determined in mm/hour based upon peak daily evapotranspiration requirements of the crop and the running time of the system. Then the application rate of the tape is derived by:

Tape application rate (mm/hour) = tape flow rate (L/hour/100 m) / 100 x row spacing (m)

Uniformity

The factors affecting uniformity are:

- manufacturing coefficient of variation (*CV)*
- sensitivity to pressure variation, known as the emitter exponent *x*

If large variations in pressure are expected, such as in long tape runs or on undulating ground with large elevation changes, then a low emitter exponent product should be selected. However, if the design is likely to have only slight pressure variations, for example short tape runs on flat ground with large diameter submains and pressure-regulating valves, then the exponent value is less critical and more attention should be paid to selecting a low *CV* product.

Clogging

The relative sensitivity of emitters to clogging depends upon many design features. Generally, large passages and high emitter flow rates are associated with less clogging potential: a 0.05' hole will reduce the effects on economic returns should the system start to clog by 50% compared with a 0.03' hole (Burt and Styles 1994). System design, installation and management can all contribute to clogging. A good filtration system with sound system maintenance should minimise the risk of clogging in most situations.

Emitter spacing

Emitter spacing depends upon the soil and crop type. It has been shown that using two laterals rather than one per bed on tomatoes increased yields (Pitts, Obreza and Almedo 1991), although yields were decreased if water was over-applied. Yield increase was due to a greater wetted soil volume being able to more easily meet crop water demand. In row crops a continuous wetted strip along the tape is generally desired. There is a scarcity of good data on the required emitter spacing to achieve this wetting pattern on different soil types. Complete wetting is also critical if germination by the drip tape is required. If drip tape 200 mm deep is to be used for germination on a clay loam then the maximum spacing is 300 mm, if 500 mm spacing is used then irrigation will need to continue until water is standing in the furrows (Burt and Styles 1994). Another advantage of closer spacings is that a greater soil volume will be wetted quicker, allowing shorter irrigation set times and making pulsing more effective if required.

Tape placement

A key decision in the design of a drip irrigation system for any crop but especially for row crops is whether to bury the tape and if so at what depth.

Surface installation

Surface installation simplifies repair to the system but needs to be removed at the end of every season. If the tape is to be reused then the tape will need to be strong enough (with thicker walls) to withstand the operation and careful retrieval will be required, requiring a large amount of labour. In tomato crops, surface retrieval of tape is difficult as it becomes entangled in the vines, although it may be retrieved once the vines desiccate. In some cases a thick-walled dripline can be passed through the harvester. Surface tape is prone to damage from machines, people, UV light, insects, foxes and other animals, as it needs to be more robust than tape which is buried. A further disadvantage is that the soil surface is constantly wetted, which promotes weed growth and can lead to disease in crops where the fruit rests on the ground such as tomatoes or melons.

Buried tape

When tape is buried the main trade-off is between being able to achieve surface wetting for germination and adequate depth for tillage operations. To maximise the upward movement of water, gravitational water movement needs to be minimised and upward sorption maximised. This can be achieved by not wetting the soil to a point where gravitational effects dominate. To promote upward wetting the emitter spacing should be as close as possible and the tape should be as shallow as possible. This reduces the maximum water flow path to the surface, which is from the emitter to the surface point half way between two emitters. There is a certain critical depth beyond which surface wetting of the soil is impossible to achieve with buried drip. This depth will vary between soils (sandy and clay soils shallower, loam soils deeper) and probably lies between 100 and 300 mm. If germination can be achieved using sprinkler irrigation or avoided entirely by the use of transplants then the tape may be installed more deeply, 300–350 mm.

Generally for germination with a good seedbed the tape should be not more than 200 mm deep and emitter spacing not greater than 300–400 mm (Hanson et al. 1997). Seedbed condition is important. The soil aggregate size and packing should be conducive to sorptive water movement. de Vries (1997) reported poor sweetcorn germination with tape at 250 mm in a very dry and loose seedbed that had poor tilth. Hanson et al. (1997) states that if tape is deeper than 200 mm with a very dry soil then germination may be difficult. Short pulse irrigations can be beneficial to promote upward water movement and hence improved germination.

Soil and water properties

The drip tape should not be installed into sodic layers where the soil structure will deteriorate upon wetting. A dispersed or generally poor soil structure with low hydraulic conductivity around the tape will result in a restricted wetted soil volume. Similarly installation of the tape into a heavy subsoil may create difficulties if the soil hydraulic conductivity properties are poor. If there is a soil textural change from lighter to heavier within the shallow root zone then the best placement for the tape may be just above the boundary.

When using saline water the tape will need to be as shallow as possible to leach the soil. Buried tape cannot leach any soil above it: this has to be done by rainfall or other forms of irrigation.

Crop types

For shallow-rooted crops the tape placement may need to be nearer the surface; lower yields have been experienced with drip 300 mm deep on onions compared with surface drip (Bucks et al. 1981). For deeper-rooted crops, the depth of placement appears less critical (Davis et al. 1985). The desirability of keeping a dry soil surface to control weeds and disease also needs to be considered.

Deep percolation

The loss of water below the root zone is likely to be greater if the tape is installed deeper. This is especially the case if frequent irrigations that maintain the soil at low potentials are applied.

Filtration

Filtration requirements

The need for a well-designed and maintained filtration system is critical to the longevity of a drip irrigation system. Drip emitters have passages as small as 0.25 mm in diameter and as such are extremely vulnerable to blockage. The greatest source of non-uniformity in a drip system after several years is usually due to emitter clogging.

A general rule for filtration design is that all particles greater than $^1/_{10}$ of the emitter passageway should be removed (Burt and Styles 1994). Filtration is designed as a stepwise process removing the largest material first and then removing gradually finer material.

In situations of large sediment load (> 200 ppm suspended solids), the first and most effective filter will be a reservoir. Reservoirs may be required with some drip systems to buffer water availability from the effluent water supply system. This is especially the case if the effluent is not supplied on a daily basis. In this case the reservoir should also be used as a sediment trap. Before the effluent water enters the pump, large debris needs to be removed with a pre-cleaner.

The choice of filter system depends upon the effluent water quality. The best filters are media filters which are pressurised tanks filled with silica sand or crushed granite. The size and number of tanks depends upon the system flow rate and the cleanliness of the water. The filters are kept clean by backflushing; this operation can require large amounts of water compared with screen or disk filters, and suitable disposal for this water needs to be found, as this will be high in nutrients and other pollutants. Media filters need to be chlorinated to control biological activity that may clog them, especially when not in use. Media filters are generally considered to be the best all-round filtration device but they are considerably more expensive than screen or disk filters, and also take up much more space.

Screen filters are generally tubular with water entering inside the tube and passing through the screen to the outlet. The disadvantage of a screen filter is that it is only 2-dimensional: there is no depth to its filtering capacity, as there is with a media filter. This means that screen filters quickly become blocked with material and so require frequent backflushing.

Disk filters are made up of hundreds of grooved disks that pack together tightly to give three-dimensional filtration. Disk filters have automatic backflushing that lets the individual disks separate and then flush with water that spins the disks clean.

System flushing

Flushing the system is extremely important in effluent irrigation, as sediment, slimes and other materials deposit in areas of low water velocity in the drip system, mostly at the far ends of laterals. This is not a problem if the tape is only to be used for one year but if a longer life is expected then regular flushing will be required. Flushing the laterals is achieved by opening the lateral ends and then pumping the material out. The key to good sediment removal is achieving a flushing velocity of at least 0.3 m/second (Burt and Styles 1994). In some cases each lateral end will be opened individually as the system is flushed, but this is labour intensive. In most cases with buried drip for row crops the ends of the laterals are joined into flushing mains which allow flushing of many laterals with a single valve. The flushing main needs to be correctly designed to achieve adequate flushing velocities. In some cases the whole system will have to be designed around the flushing requirements if the flushing flow rate greatly exceeds a design flow rate. However, with some designs the flushing flow rate may be less than the design flow rate. If this is the case then the flushing pressure of the system is controlled by the number of laterals flushed at once. If the flushing flow rate is higher than the design then the flushing pressure needs to be determined and main lines, submains, manifolds designed accordingly. The tape selection also needs to ensure that the bursting pressure will not be exceeded.

Chemigation

Chemical injection is a fundamental part of drip irrigation. Most if not all fertiliser must be applied through the system in order to reach the roots. Even with effluent water supplies it is likely that some fertiliser application will be required. Apart from fertilisers, other chemicals need to be applied through the system to keep the laterals and emitters clean. Although there are currently restrictions in place, in future there may also be the possibility of applying herbicides, fungicides and nematicides through the system. Soil or water ameliorants can also be applied through a drip system.

Crop fertilisation requirements and the choice and timing of fertilisers is a complex area requiring agronomic skills, basic chemistry and a good understanding of the costs and benefits of each decision. Fertigation offers many advantages compared to conventional fertiliser application methods:

- Nutrients can be distributed more uniformly across the paddock.
- Nutrients can be supplied incrementally through the crop life cycle matching delivery with need.
- Nutrients are supplied directly to the root zone so they should be used more efficiently.
- Nutrients can be applied when conventional equipment cannot enter the paddock.
- Crop damage, such as leaf burn, associated with the conventional methods is avoided.
- Less labour is required than with conventional methods.
- Less machinery is required than with conventional methods.

All the chemicals used in a drip system must be soluble. Fertilisers can be bought already in solution and directly injected. Dry fertiliser must be mixed with water into a solution before injecting.

When using several fertiliser and other chemicals within a drip system, care must be taken that the various compounds are compatible. This compatibility must also be considered in terms of the constituents already present in the effluent water. When fertilisers or chemicals are mixed, it is essential to avoid creation of toxic gases, heat generation, creation of precipitates or slimes that will clog the system or creation of phytotoxic mixes. Fertigation should be installed upstream of the filter system.

Nutrient distribution under a drip system depends upon the wetting pattern, soil type and rate at which the effluent water and any fertiliser is applied. Nitrate is highly mobile and will distribute in proportion to the water movement. Thus, nitrate will be lost by any deep leaching and will accumulate above the tape line where water is preferentially extracted by the crop. Ammonium tends to be strongly adsorbed onto the soil and thus does not move as readily as nitrate: after some time, the ammonium converts to nitrate. Phosphorus tends to be adsorbed by the soil and thus may not distribute evenly through the root zone. Potassium fertilisers are quite soluble but are easily adsorbed so they will have restricted movement. Higher concentrations will promote greater distribution. As nutrients are applied with the water, a good system distribution uniformity is required.

IRRIGATION REQUIREMENTS

Calculating irrigation requirements

The irrigation requirement has been defined as being equal to the difference between the crop water requirement and the depth of rainfall at a location (Allen et al. 1998). The problem with the definition is the determination of the crop water requirement. Rainfall can be measured using standard meteorological equipment, but the crop water requirement is much more complex. This section will summarise the methods used and the factors that affect the calculation of the crop water requirement.

The final determination of the irrigation requirement will also include a component for the leaching requirement and the system uniformity. More water has to be applied to control the salt concentration in the soil profile, as irrigation water quality becomes impaired by the addition of salt and other elements. This is termed the **leaching requirement** and is a function of the soil salinity, the crop salt tolerance, the crop growth stage, and the quality of applied water.

Distribution uniformity, as discussed previously, is a function of the irrigation system type and management. As the uniformity gets poorer, additional water is applied to ensure that all portions of the field receive the required depth of application. Frequently, the inefficiency in the irrigation system provides adequate deep percolation to meet the leaching requirement and an additional depth of water is not included in the calculation of the irrigation requirement.

Crop water requirement

The crop water requirement is the water required to compensate for the evapotranspiration loss from a cropped field. This is the net value of the water to be supplied, that is, the minimum that will not result in crop water stress. Evapotranspiration (ET) is the combined loss of water by evaporation from the soil and plant surfaces and the transpiration by the plant.

Evaporation losses from free water surfaces are affected by air temperature, radiation, humidity, and wind speed. Soil evaporation losses are also affected by the amount of shading, the water availability at the soil surface, the soil water content, the soil type, and the depth to shallow groundwater. For example, fine-textured soil has the capability of transmitting water from deep within the soil profile if the evaporative demand is low. As the soil surface dries, the potential loss drops significantly because the hydraulic conductivity is reduced and the flow is also reduced.

Crop transpiration is the vaporisation of liquid water contained in plant tissues and the removal to the atmosphere. This is done primarily through the stomata, which are the small openings on the plant leaf through which gases and water vapour pass. Water is taken up by the roots and transported through the plant and to the leaf where the exchange occurs. The stomata control the vapour exchange between the intercellular space and the atmosphere. Nearly all the water taken up by the plant is lost by transpiration with only a tiny fraction being used by the plant.

Transpiration depends on the same factors as evaporation to drive the process. This means that radiation, humidity, wind speed, temperature, and vapour pressure gradient have to be included in the determination of transpiration. Other factors affecting the transpiration include crop type, variety, developmental stage, canopy roughness, rooting characteristics, crop height, percent groundcover, plant stand, and resistance to transpiration. Waterlogging may reduce transpiration due to root damage and poor plant health from anaerobic conditions in the root zone.

Management and environmental factors also may have a significant effect on evapotranspiration through plant health and water availability. Crop development and ET may be limited by salinity, poor land fertility, poor plant nutrition, pests, compacted soil layers, impenetrable horizons. Windbreaks may reduce ET in a field by limiting the wind run across an area. Use of mulches will also contribute to reduction in evaporation. Early in the development of orchards significant water is lost to evaporation from the bare soil after surface irrigation or sprinkler irrigation. This is less of a problem after the trees are fully developed and the area is shaded. Limiting the wetted surface area through the use of drip irrigation will reduce evaporation losses.

The standard crop water requirement is estimated by multiplying ET_o by a coefficient that has been developed to account for the effect of crop age and development on water use. The equation is $ETc = Kc \times ETo$

where ET_c is the standard crop water use, and K_c is the crop coefficient.

Crop coefficients have been developed by researchers throughout the world based on lysimeter studies and water balance studies of crops. The equation for the crop coefficient is $Kc = ETc / ETo$

where the evapotranspiration of the crop has been measured by a lysimeter and the standard evapotranspiration has been calculated using the Penman–Monteith equation. These data were used to develop the coefficients found in FAO 56.

The crop coefficient has been approximated as a linear function that characterises the following four growth stages: initial, crop development, mid-season, and late season. The first stage typifies mainly soil evaporation, the second characterises the groundcover development, the third reflects the crop type and canopy structure, and the last reflects the crop type as related to the harvest date. Tables detailing these growth stages are available for a wide range of crops in FAO 56 (Allen et al. 1998). The application of this method is also detailed in this publication.

Most crops are not grown in standard conditions, so methods are provided to account for non-standard conditions. Evapotranspiration is calculated by applying an additional coefficient to the standard equation. The resulting equation is

$$ETc = ETo \times Kc \times Ks$$

where K_s is a stress coefficient. The stress coefficient accounts for water stress due to under-irrigation, stress due to salinity, and waterlogging.

Adjustments can be made to the crop coefficient to account for the percentage of area covered by the plants, percentage of wetted area, time between wetting events, and whether it is an annual or perennial crop. Also, procedures have been developed to account for missing weather data.

The above procedure has been described as the single coefficient method. There is also a dual coefficient method that describes the basal transpiration and the evaporation component. This more complicated than the single coefficient method and is generally more applicable to research applications. The use of the FAO method will give reasonable estimates of the crop water requirements when calculated with local weather and cropping data.

Further reading

FAO Irrigation and Drainage Paper No. 56, *Crop evapotranspiration (guidelines for computing crop water requirements)* by Richard G. Allen, Luis S. Pereira, Dirk Raes, Martin Smith, 1998.

SOIL MOISTURE MONITORING

Fundamentally crop growth relies upon the availability of water. For many crops, the water used has shown a direct relationship with dry matter production. This relationship varies from crop to crop and also depends upon climate. The effect of any water limiting periods on crop yield depends on their timing and duration in relation to the crop growth stage. Avoiding crop stress due to inadequate water is the reason for irrigation. Soil water measurement should be an integral part of any irrigation farmer's cropping practice for the obvious reason that it is within the farmer's power to alter the moisture status of their soil.

Measuring soil water is useful in three areas of crop production:

- assessing if the soil is too dry for optimum crop production in terms of yield and quality – when and how much to irrigate?
- measuring the uniformity of soil water – due to soil variability and non-uniform irrigation
- crop nutrition – nutrient availability for crop uptake depends upon the soil moisture status and keeping those nutrients in the root zone.

Soil water measurement is also essential to the long-term sustainability of irrigation. The environmental effects of over-irrigation are pollution of groundwaters and creation of shallow watertables and subsequent waterlogging and salinisation. This threatens the viability of most effluent irrigation schemes in arid areas around the world. Over-irrigation in this sense can be defined as 'water passing below the root zone' – in other words, water lost down and out of the plant roots' reach.

For the above reasons, soil moisture measurement is of vital importance for irrigated farming, and more so if recycled/reclaimed water is used because of increased risk of pollution of groundwater due to contaminants. The role of irrigation in producing quality crops is better understood and better appreciated by farmers striving to meet quality criteria for manufacturers and exporters who have to increasingly comply with international environmental standards.

There are many methods for measuring soil water content including tensiometers, gypsum blocks, capacitance probes, time domain reflectometry, neutron moderation and heat dissipation techniques. There are also wetting front detectors that indicate when to stop irrigating. This is a large and important topic that has been recently reviewed in detail to

include the method of operation and manufacturers by Charlesworth (2000). In this section the focus is on system selection objectives, positioning and interpretation of data.

Each system has merits and problems that will not be discussed here. We will merely highlight the important criteria that should be considered when selecting a system.

The objectives of soil water monitoring will determine the level of precision and expense warranted in a soil water monitoring system. Typical objectives can be:

- to investigate if existing irrigation practices are adequate
- to facilitate a decision on which crop or paddock to irrigate next
- as a check on irrigation scheduling by evapotranspiration methods
- to be used as the only system to decide when and how much to irrigate (not recommended)
- to produce an increase in crop yield and/or quality
- to be used to automatically control an irrigation system
- to maximise the return from irrigation in areas of limited supply
- to reduce water and nutrients moving past the root zone.

If recycled/reclaimed water is used for irrigation it may become mandatory to undertake soil water monitoring as part of the conditions of use. In this case the main focus of concern will be that the water is being used by the crop and not leaking excessively to the groundwater with potential pollution.

Design of the monitoring system

The ease with which plants can extract water from the soil is a reflection of the soil water potential. In this regard, measuring soil water potential reflects the stresses the plants are experiencing, but there are drawbacks. The main difficulty is the lack of automated maintenance-free systems for monitoring soil water potential. Systems using absorbent blocks come closest to meeting these criteria at present. Measurement of matric potential will indicate when an irrigation is required but not the amount of water in units of volume e.g. mm or litres/plant. Thus the soil water deficit in mm has to be estimated from the measured soil water potential. Many probes measure water content and this can be related to some field estimates of field capacity and wilting point.

Importantly for those assessing water movement below the root zone, water movement in soils can only be estimated by measuring soil water potential, although it can sometimes be inferred from volumetric readings at small time steps.

The system around the sensor may be a portable unit or permanently installed in an access tube or buried. The measurements may be manual or by automatic logging. Some systems may incorporate automatic logging and downloading of the whole farm data to the office.

Portable systems are generally cheaper than fixed systems but require more labour. Portable systems should use permanently installed access tubes. Instruments that are pushed into the ground on a random basis have the disadvantage in that soil bulk density and texture then become variables that make interpretation difficult. The other difficulty is that it is impossible to return to exactly the same spot, and this will mask changes over time, making this a random reading which will require many replicates to give a representative sample.

Automatic datalogging is becoming commonplace but is not essential. A consideration is whether the irrigation system is flexible enough to make irrigation decisions on an hourly or daily time step. Logging and then data review on a small time step is an interesting learning process initially. Logging reduces the labour requirement to collect soil water content data, but it still takes time to review and requires familiarity with computers.

Consideration should be given to the flexibility of the system. Can it be moved easily? What is the installation procedure? Is it suited to all the soil types irrigated and crops grown? Often automatic logging systems require much cabling to connect sensors to loggers which can easily get damaged. However, this is now being addressed with the development of radio (wireless) links. Can the system be used to automatically control the irrigation system? The cost of the system should be considered on the number of hectares or crop varieties that can be covered. This is a function of labour requirements on single instrument and manually read systems. With logging systems this depends upon the number of sensors allowed per logger. The overall cost of the system has to be offset by a gain which may be increased yield and quality or reduced water use or reduced labour.

Where to monitor

In regard to all that follows on positioning of soil moisture sensors there are two essential criteria that must be remembered:

1) the site must be easily accessible, and 2) the equipment must be protected from machinery damage.

When selecting sites for soil moisture monitoring it is important to consider the irrigation practice. If a paddock can only be irrigated as a whole, then there is little benefit in splitting it into many separate moisture monitoring units. This does not mean site variability should be disregarded. A general requirement for any soil monitoring site is that it must be representative of the crop and soil within that management unit. Crops are often split up in terms of age, variety or planting date, and may each have different irrigation requirements. If soil type varies greatly within the crop, then several sites may be required, or an 'average' site selected. Discovery of soil variability may lead to a change in the management units so that each soil type can be managed better.

Irrigation system distribution uniformity

Knowledge of the irrigation system and its distribution uniformity are essential for site selection.

Flood irrigation applies different amounts of water at the top, bottom and middle of bays or furrows. Thus in flood irrigation it is likely that soil water measurement will be as much to do with measuring aeration stress as measuring water stress. This often necessitates multiple sites down a row or bed to give an indication of the irrigation uniformity.

Solid set sprinkler systems are more likely to apply the water uniformly over the crop area, but there are areas of minimum and maximum precipitation.

Moving irrigators are subject to the same sprinkler uniformity problems, with the added non uniformity of varying travelling speed.

Other irrigation systems such as drip or microjets distribute the water to a crop with a high degree of uniformity.

When monitoring soil moisture for an irrigation system which has low distribution uniformity, there is a dual role of scheduling each irrigation and also assessing attempts to improve the uniformity. Irrigation systems with low distribution uniformity will require more soil moisture monitoring sites for a useful interpretation of 'average' soil water status than those with a high uniformity.

Sensor positioning

The sensor positioning should allow an estimation of when and how much to irrigate. This is best done by selecting a position that reflects the 'average' root zone conditions.

The average root zone conditions are most useful, because, if a drier area is selected, then over-irrigation can result, and if a wetter area is selected, under-irrigation can result. The average conditions are required when checking soil water conditions against evapotranspiration calculations. There should always be a sensor at the bottom of the root zone to see if drainage is occurring below the root zone. Selecting the most useful sensor positioning is an iterative process and the results need to be continuously analysed to assess whether conditions have changed and a new sensor position is required.

Depth

Crop water extraction is often idealised as 40% from the top ¼ of the root zone, 30% from the next ¼, 20% from the next ¼, and 10% from the bottom ¼. To measure the average rootzone water content, then, the sensor should be placed on the boundary of the second and third quarter. This will best represent the soil water deficit as predicted by evapotranspiration estimates. If multiple sensors can be used, then the soil water deficit in the root zone can be measured more accurately.

It is important to remember that a plant will dry the soil from the top down, and the bulk of roots are shallow. If sensors are installed into an existing crop, then the root distribution can be investigated by excavation. In annual crops, sensors are installed where most roots are expected to be: this is usually in the best structured and most fertile area, usually the top 30 cm, especially when crops are young. When the crop has matured, then water use may be significant deeper in the profile, as in cotton. In this case deeper sensors are required to monitor root development. Root development varies with different crops and soils and the zone of maximum extraction varies with the crop development. Soil water sensors placed in areas without roots are of little value. Optimising the sensor position is an iterative process of trial and error.

One sensor should always be installed at the bottom of the root zone. This sensor will indicate if the crop is over- or under-irrigated. Ideally after irrigation this sensor should wet back up to field capacity and no more. Wetting beyond field capacity indicates drainage past the root zone, causing loss of nutrients and recharging watertables. No re-wetting indicates that the root zone has not been completely refilled and the crop will become stressed more quickly.

Soil moisture monitoring systems that allow measurements at many positions down the profile allow for a better understanding of root development and drainage past the root zone.

Positioning relative to the plant

In most situations soil moisture measurements are taken in or very close to the crop row. This is because most roots develop directly under the plant: this is the case when most or all of the soil surface is wetted during irrigation. Some irrigation systems however do not apply water to the entire soil surface (such as drip, microjet or some furrow systems). This adds another layer of complexity to sensor positioning. As discussed earlier, roots grow where there is moisture, and thus most roots will be within the wetting pattern of the irrigation system. Irrigation systems such as drip or microjet are in effect 'point sources' of water that are often designed to act as a 'line source'. However, there will generally be most water applied near the dripper outlet or microjet sprayer and least water applied halfway between the outlets. The roots of the plant may reflect this water distribution. In the case of drip irrigation the soil area close to the dripper outlet remains saturated for long periods and as such roots do not tend to grow strongly in this area.

If the water application system is behaving as a line source then the soil moisture sensors need to be placed somewhere between the plant and the water source. In furrow-irrigated orchards water is usually applied some distance away from the trunk of the tree, the area around the trunk of the tree remaining quite dry. In this case most root activity will be near the irrigation source and not near the base of the tree.

With irrigation systems behaving as point sources, the source is usually located near the plant. The soil moisture sensor is then placed somewhere between the wettest and driest part of the wetting pattern, often one-third the spacing away from the plant.

The best method of ascertaining root distributions is by excavation. Significant rainfall in the growing season can lead to high root densities away from the wetting pattern of the irrigation system.

With non-uniform irrigation systems the wettest soil and point where most drainage will occur is directly below the outlet. Thus, sensor positioning to monitor the maximum drainage past the root zone should be directly below the water source. This is a quite different position to that of the 'average' root zone.

Number of sensors

The number of sensors required to adequately represent the soil water status in a crop depends upon the heterogeneity of the soil and crop, the uniformity of water application and the soil water sensing system. For vegetable irrigation purposes we are interested in soil moisture changes over time and so follow carefully a few sensors that give a representation of the whole field or crop. The cost of the sensors and of their maintenance and reading will finally dictate the number of sites. Sites must be selected subjectively to give an adequate representation of the whole management unit and the results assessed against the performance of the whole unit.

Timing of soil water content readings

The timing of soil water content readings controls the degree of interpretation and understanding of the system that is possible. How often readings need to be taken is a function of the predicted daily evapotranspiration, soil type, depth of root zone and the irrigation system. Obviously at periods of low evapotranspiration fewer readings need to be taken.

Root zones with low available water capacities will require more frequent readings as depletion will occur more quickly than in root zones with large amounts of available water. The available water depends upon the soil type and root depth. Young crops require more frequent irrigation, and thus monitoring, due to a limited root zone, than mature crops.

The irrigation system is important, as there is little benefit in high frequency soil water content readings for a system that can only apply water at a much lower frequency. Flood irrigation is labour intensive and thus daily waterings are usually not attempted; also, the amount of water applied by flood irrigation is difficult to control, and small daily amounts almost impossible. Pressurised systems require less labour to run and varying amounts of water can be easily applied with different set times. Different systems have different application rates: for example, drip irrigation applies water at rates less than 5 mm/hour , sprinklers at rates of 5–20 mm/hour and flood irrigation at the maximum intake rate of the soil, up to 100 mm/hour initially. Thus different amounts of time will be required to replace depleted water. Also, the minimum amount of water that can be applied can dictate the frequency of reading required. Drip systems can be run for fractions of hours; sprinkler systems usually have a minimum time to achieve reasonable uniformity; and flood systems have a long soil contact time. These are management and system design problems. With automated soil moisture sensing systems, frequent readings come at no extra labour cost, whereas manual readings are expensive.

The frequency of reading should be adequate to predict when the next irrigation will be required with an adequate lead time. With flood irrigation it may take a day or two to set up for the irrigation – with drip, a few minutes may be all that is required. Availability of water is important in this regard.

The soil water content should always be monitored after an irrigation or rainfall event. This gives a check on the irrigation, ensuring that the depletion has been replaced as required and that excessive drainage did not occur, or gauges how much of a rainfall was effective.

In general soil water readings should be taken at the same time each day, preferably in the morning to allow water redistribution to occur overnight.

Interpreting soil moisture sensor readings

Soil water content data must always be recorded over time. Individual readings without a previous record are of limited use, and thus a graphical representation is most useful. When a new water content measuring system is installed there should be no change in irrigation management for the first few irrigations. This is purely a monitoring phase. Later when the meaning of the data is clear, feedback can begin to alter irrigation intervals and amounts.

On a soil water content graph, as for any irrigation scheduling system, there are two soil water contents that need to be estimated: the 'full point' (field capacity) which is the upper limit of soil storage, and the 'refill point' (maximum allowable deficit) when irrigation should occur. These points can be estimated by the rate of change in water content of the soil. The full point can be estimated after the soil has been wetted to saturation and the soil has drained by gravity. Plant water use does occur at water contents above the full point and so if a crop is actively growing this point is harder to estimate. Water applied to the soil above the full point will drain to the next layer. If this occurs at the base of the root zone then the water is wasted. Plant water use then dries the soil: this occurs rapidly at first, and gradually slows as the soil matric potential increases. At some point the rate of water extraction is sufficiently slowed that the plant is now expending significant energy on water extraction. This is taken as the refill point.

The refill point will vary enormously and is often quite subjective. Refill points vary with crop type, stage of growth, quality criteria, management limitations and irrigation water availability.

With drip irrigation, crops are often kept very close to field capacity (i.e. frequent irrigations with small amounts) in order to maximise growth rates. This can be achieved and automated by a sensor in the shallow root zone that controls the irrigation to maintain the soil moisture at almost a constant level.

The degree with which the whole soil root zone is represented is important in setting refill points. Shallow soil layers will dry out quickly; if the water can be replaced frequently in these layers without excess drainage then irrigation can be scheduled on those layers. After the shallow layers dry out, water use moves deeper: if information on the deeper layers is available, then irrigations may be scheduled on the deeper layers, but the energy of extraction from deeper layers is higher and thus the refill point would have a lesser value than for the shallower layers. The timing of irrigation is an integration of the whole root zone water content to achieve a desired agronomic outcome. This requires experience and judgement.

Thompson (1996) outlines a decision support system for interpreting soil moisture sensor readings. This system assesses the sensors themselves as well as irrigation timing and drainage. If the sensor values are static then the sensor is not in an active part of the root zone or poorly installed, that is, isolated from the roots somehow, and should be moved. It may also be broken. Other sensor checks are whether the sensor readings are within the expected range of that sensor and the soil. Also if deeper sensors wet up before/quicker than shallower sensors there may be problems of preferential flow through the soil or around the sensor. This may be a natural phenomena in a cracking soil. If multiple sensors are used, then extreme values are questioned.

The rootzone depth is assessed by finding the deepest sensor with significant water use. Then the average water content of the root zone is calculated and compared to the refill point. After an irrigation, the system checks that the whole profile is refilled and no excessive drainage has occurred. This logic is what is required when assessing soil moisture readings. When interpreting soil moisture readings a knowledge of the plant, water movement and storage in soils and the principle of operation of the sensor is required.

DRIP IRRIGATION SCHEDULING

With drip irrigation the system has the potential to very closely match plant water use on a daily basis. This is very different from other irrigation methods where an assessment of soil moisture storage is made and at a maximum allowable depletion the crop is irrigated. With drip irrigation, scheduling should be evapotranspiration-based; put simply, the crop evapotranspiration from the previous day is estimated and replaced the following day. A soil moisture depletion approach is difficult since the estimate of the total soil moisture available relies on knowing the soil wetting pattern, and this is difficult to accurately quantify under drip. The other drawback to the soil moisture depletion method is that the drip system is not designed to replace large soil moisture deficits quickly as can be done with furrow irrigation. The maximum allowable deficit under drip irrigation is a single day's evapotranspiration or less during peak season. Phene (1995) shows that high frequency surface drip irrigation results in higher yields of tomatoes than low frequency surface irrigation but the best yields were obtained with high frequency buried drip. On corn, Caldwell, Spurgeon and Manges (1994) found no correlation between yield and deficits between 13 mm and 51 mm irrigated every 1 to 7 days. So a simple statement of irrigation scheduling with drip irrigation may be to maintain the main root zone at a low soil water potential without creating aeration or disease problems or creating excessive deep percolation.

Maintaining low soil water potentials requires frequent irrigations. The use of soil water sensors directly linked to the system controller can turn pumps on but there needs to be manual oversight of such automation. There is also a need to check that water is not lost from the root zone, and thus a soil moisture sensor placed at the bottom of the root zone can be used to turn pumps off and check that losses are minimised.

With drip irrigation, especially buried drip, soil evaporation is reduced compared with furrow irrigation, but crop transpiration is increased and as such total evapotranspiration with drip irrigation can be expected to be higher.

Since buried drip irrigation can be highly efficient in matching the crop water needs, the leaching requirement should be considered. Above the dripline, leaching must be achieved by rainfall or an alternate irrigation method. If this leaching occurs by rainfall, then the salts may be washed down into the main root zone. However, the root zone will be maintained at low water potentials during the main crop growth period and so it is unlikely that there will be any effects of salt when using good quality irrigation water. The area below the drip tape is maintained at low soil water potentials and in normal circumstances water will be over-applied: thus there is a tendency for downward movement, and leaching will occur.

The frequency of irrigation with drip is often daily, but can even be many times per day. Irrigation with drip needs to be on a frequent basis as the root zone is limited to the wetted area which in turn is much reduced compared with furrow irrigation. For shallow-rooted crops (such as onions or lettuce), irrigation should be once per day or twice per week. During peak season irrigations tend to be once per day by necessity to replace the daily evapotranspiration, else a large soil moisture deficit will occur that the system cannot replace.

Soil moisture measurement is essential with drip irrigation to ensure that an adequate soil wetted volume is maintained. Scheduling assumptions by evapotranspiration and crop coefficient do not consider the wetted soil volume, and it is important to maintain the wetted volume as a buffer against peak demand. If the wetting pattern is allowed to contract early in the season there may be no effect on the crop, but when high crop water demand occurs there may be insufficient soil storage. If a wetting pattern contracts it is difficult to re-establish, as the crop is using water, and the drying soil has a lower hydraulic conductivity to redistribute water away from the emitter.

The actual soil water content, refill point and full point are of less importance with drip irrigation: the main consideration is the soil moisture trend. If soil moisture content is gradually decreasing, then irrigations should be increased; if it is increasing, then irrigations should be reduced. The soil water content should be measured in the middle of the rootzone, at the edge of the desired soil wetted pattern, and at the bottom of the root zone. The point in the middle of the rootzone is used for scheduling, the point at the edge of the wetted pattern is to ensure that adequate wetted volume is maintained, and the point at the bottom of the root zone is to provide information on how much drainage is likely to be occurring.

Soil wetting patterns

The soil wetting pattern under a drip system is highly variable depending upon soil type, system design and management. As discussed in the above section an adequate wetted volume is essential. Using the 'Wetup' program (http://www.clw.csiro.au/products/wetup/) we can demonstrate the differences between soils. Figure 4 shows the soil wetting pattern on a sandy soil. Most of the wetting is below the tape and lateral wetting is restricted. Figure 5 shows the soil wetting pattern on a clay soil. The wetted area is much wider and deeper than with the sandy soil.

Figure 4 – Soil wetting pattern on a sandy soil

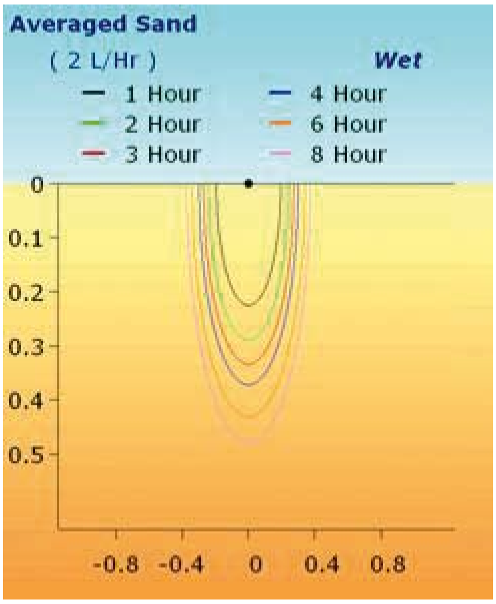
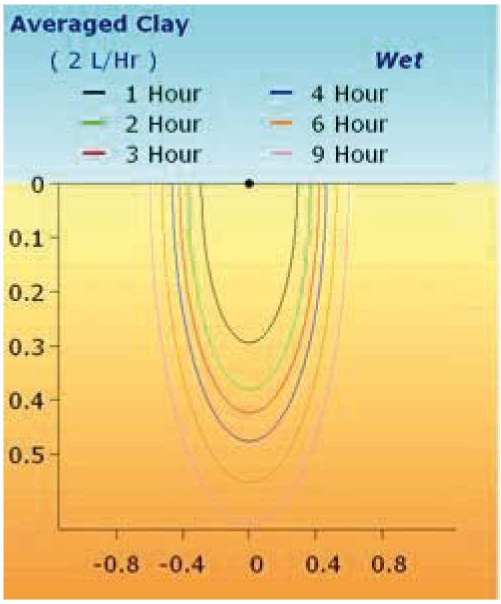


Figure 5 – Soil wetting pattern on a clay soil



Deep percolation is a common, almost inherent, phenomenon with drip irrigation because of the uneven wetting pattern. The very wet zone below the tape is likely to lead to deep percolation. This has been shown with sweetcorn on beds in a loam over clay in the MIA (de Vries 1997). In this trial, the soil below 500 mm remained saturated for long periods and it was found that it took water 1 to 2 hours to reach 800 mm depth after the start of an irrigation whereas it took more than 24 hours to travel 500 mm laterally at the tape depth (200 mm). Measurements of wetting patterns under a surface drip system in a MIA vineyard revealed similar patterns (Cox 1995).

SECTION 5 – WATER QUALITY: EFFECTS ON IRRIGATION EQUIPMENT

CORROSION

To limit corrosion of pipework, irrigation water pH should be in the range of 6 to 9. Besides corrosion high or low pH water can potentially adversely affect crop growth. Low pH can mobilise toxic ions such as aluminium and manganese. High pH can affect plant growth by reducing the availability of nutrients.

Corrosion of pipework is a common problem in agriculture in Australia. Corrosion can be by chemical, physical or microbiological processes. These can corrode not only metals but also in some circumstances concrete and plastic. Wastewater is generally of neutral pH, unless it contains high levels of food processing wastes, and as such is not likely to present corrosion risks.

FOULING

Irrigation systems can have serious problems related to the supply and distribution of water due to water quality. Poor water quality can result in clogging, encrustation and scaling (Table 13). This can reduce the performance of the system by reducing the capacity of the system to apply water at the required rate, reduce the distribution uniformity of the system and increase pumping and maintenance costs. The risks associated with fouling are of particular concern for drip irrigation systems due to their low flow rates and small pipe/aperture sizes that make them prone to clogging.

Table 13 – Fouling in irrigation systems, principal causes

Parameter	Description
Physical	Accumulation of sand, silt, clay and organic matter causing clogging
Chemical	Precipitation of chemical compounds casuing scaling, blockage of emitters
Biological	Blockage of pipes, filters and emitters due to growth of organisms within the system or organisms present in supply water

Source: modified from ANZECC 2000

Physical causes of fouling are often due to sand and sediments accumulating within systems; this also applies to surface irrigation systems. With wastewater, organic materials are the main suspended matter. This is not usually a concern with surface systems but can cause major problems for pumped systems, especially drip systems.

Chemical precipitation results from excess of calcium, magnesium, carbonates, sulfates and iron. This precipitation is usually seen as scale build-up, commonly caused by the degassing of carbon dioxide from the water. Risk of precipitation of carbonate compounds can be assessed by the water hardness and the log of the chloride to carbonate ration. Iron and manganese precipitation is usually not a problem if pH is maintained between 5 and 9. However, this is also influenced by levels of CO_2, sulfur, organic matter and micro-organisms. Waters with elevated levels of iron should be treated as high risk and special analysis undertaken to assess the fouling potential.

Microorganisms such as bacteria, algae, slimes and fungi can cause biofouling in all types of irrigation systems. In wastewater systems the most common type of fouling will be organic, due to the high level of available nutrients. Other types of biofouling due to iron or other metals is more commonly associated with the use of groundwaters rather than wastewaters. There is also often associated fouling in the form of chemical precipitation and entrapment of particulates.

Particular problems with algae in irrigation water supplies are the blockage of filters for drip irrigation systems. There are also some risks associated with sprinkler application of water with extremely high algal loads as this can result in a smothering of the crop.

WATER QUALITY FOR DRIP IRRIGATION

As drip irrigation is particularly prone to blockage problems it is useful to give some specific guidelines. Table 14 has some guidelines on water quality criteria for drip systems.

Table 14 – Guidelines for potential problems with irrigation water for drip systems

	Potential for problems		
Type of problem	Minor	Moderate	Severe
Physical			
Suspended solids (ppm)	<50	50–100	>100
Chemical			
pH	<7	7-8	>8
Total dissolved solids (ppm)	<500	500–2000	>2000
Bicarbonate (ppm)	<100	100–350	>350
Manganese (ppm)	<0.1	0.1–1.5	>1.5
Iron (ppm)	<0.2	0.2–1.5	>1.5
Hydrogen sulfide (ppm)	<0.2	0.2–2.0	>2.0
Biological			
Bacterial population (no/L)	10 000	10 000–50 000	>50 000

Notes 1. Bicarbonate concentrations exceeding 2 meq/litre and pH greater than 7.5 can cause calcium carbonate precipitation.
2. Bicarbonate concentrations exceeding 2.5 meq/litre can cause precipitates when injecting phosphate fertilisers.
Sources: Hanson et al. (1997)

All drip systems require a filtration process in order to prevent blockage of the drip emitters which have apertures as small as 0.03 mm diameter. For solids it is a general rule of thumb that all solids greater than one-tenth the size of the emitter should be removed to prevent bridging, i.e. 0.003 mm. For microsprinklers with simple orifices, removal of particles one-seventh of the orifice diameter is considered sufficient (Burt and Styles 1994). The filtration system is expensive and uses high hydraulic pressure, making the process expensive.

Most filtration systems can manage water with up to about 200 ppm suspended solids. If the water has greater suspended solids than this, then some pre-treatment will be required, often in a settling reservoir. Algae is a particular problem in that it floats and rapidly blocks filters, especially filamentatious-type algae. If there are high algal loads then pre-treatment in the reservoir is required to kill the algae and allow the dead algae to sink.

Apart from suspended solids, precipitates in the pipe system and growths of micro-organisms are particular problems, especially in high nutrient environments. Iron and manganese oxides are also caused by bacteria. These problems can be overcome by injection of chlorine into the drip system to kill the micro-organisms. This can be continuous at a low level (1–2 ppm) or periodic dosing at high concentration (10 ppm). Calcium and magnesium carbonate precipitation can be a serious problem and is usually overcome by injection of acid (sulfuric or phosphoric) or injection of SO_2. By dropping water pH to 6.5, carbonate precipitation is prevented. For detailed information on the filtration and management of drip and microspray systems refer to Burt and Styles (1994) and Hanson et al (1997).

Further reading

McLaughlan, RG, Knight, MJ, & Stuetz, RM, 1993, *Fouling and corrosion of groundwater wells: A research study*, National Centre for Groundwater Management, University of Technology, Sydney.

SECTION 6 – MANAGING DEEP DRAINAGE

Globally, irrigated agriculture leaks water and solutes beyond the root zone. In Australia, water leaking beyond the crop root zone, or *deep drainage*, is made evident by widespread shallow (<2 m) watertables throughout the major irrigation areas of south-eastern Australia. Horticulture can be particularly susceptible to high levels of deep drainage because the crops are often shallow-rooted, the soils used are often light soils that drain freely, and there is a need to maintain high soil moisture levels to achieve high crop quality.

Deep drainage creates serious problems of waterlogging and land salinisation. In many horticultural areas in Australia and around the world, the problem has been so great that many farms are now protected by expensive subsurface drainage systems that control local watertable heights and rootzone salinity. In effluent irrigated systems controlling leakage below the root zone has further critical importance in preventing groundwater contamination that may occur due to the presence of high levels of nutrients and other contaminants.

Each location presents a series of minor obstacles to be overcome in order to monitor deep drainage, defined as that water which moves below the root system. However, the first obstacle is the same everywhere – to define the extent of the root system. The maximum vertical extent of this root system must be known in relation to the location of any soil water monitoring device before any conclusions can be made about the occurrence or volume of deep drainage. There are four ways of obtaining estimates of root zone extent that are divided into destructive and non-destructive methods. Destructive methods include digging soil pits and soil coring. The non-destructive methods are soil moisture monitoring and soil penetration resistance.

Soil moisture sensors can be used to map the root zone extent. For devices such as a neutron probe, profiling capacitance sensor or an array of gypsum blocks a season of data is required to determine the zone of water extraction due to the frequency of measurements. However, with the aid of high frequency logged soil moisture data the root zone extent can be mapped within a few days by observing the diurnal changes in soil moisture.

The extent of the root zone is identified as the maximum depth where steps of daytime water extraction are visible.

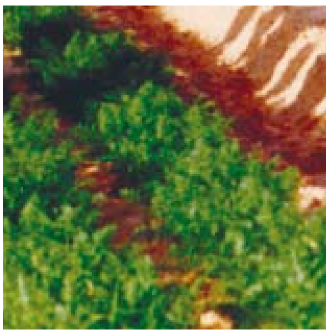
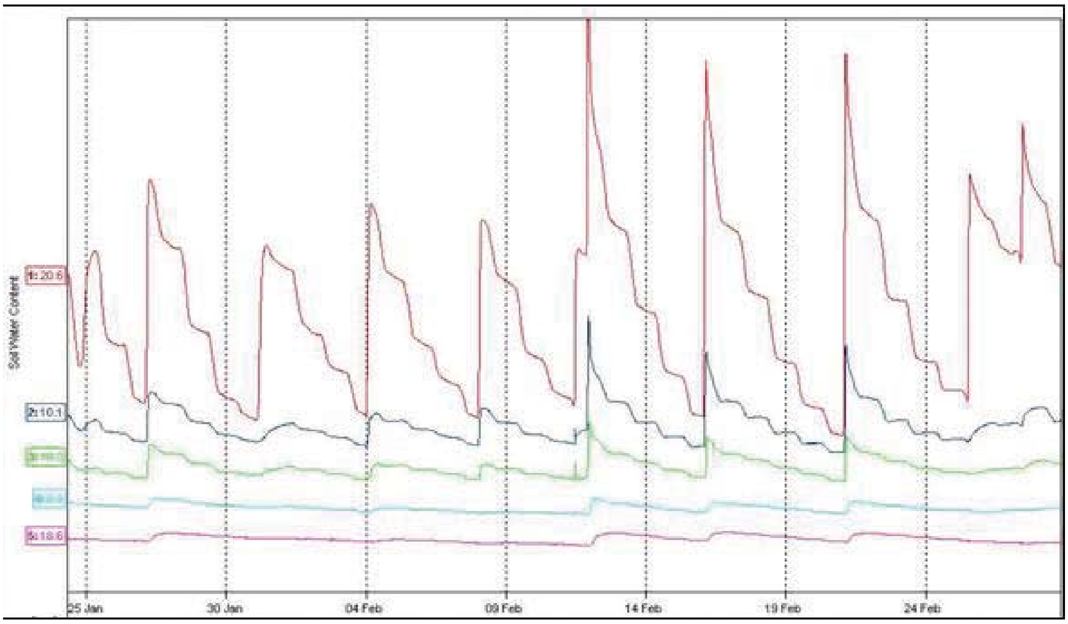


Figure 6 – Soil moisture monitoring data from a capacitance probe



Note where the lower layers show no diurnal fluctuation.

Figure 6 shows data collected with a capacitance soil moisture sensor. The rooting depth is 70 cm, because the amplitude of the diurnal steps cannot be identified beyond this depth.

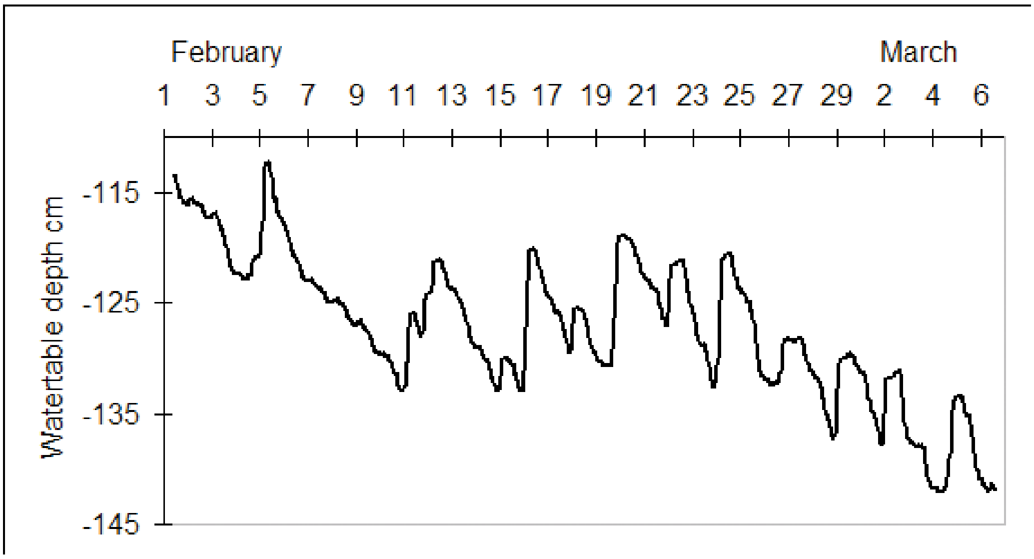
DEEP DRAINAGE MEASUREMENT

The method selected to monitor deep drainage depends on the proximity of the watertable to the root system, the level of complexity and the required accuracy. For applications where there is a shallow watertable (<2 m) deep drainage is most easily observed by monitoring the watertable height in a test well. A 3 m long PVC tube is slotted for its full length, covered with a fine mesh sock and installed in a vertical hole in the soil.

The water level in the test well follows the rise and fall of the watertable in the soil. This data can be measured manually with a plopping bell or recorded with water level sensor. The volume of deep drainage is given approximately by the height of the watertable rise multiplied by the air-filled porosity (AFP) of the soil above the watertable. To obtain an accurate estimate of deep drainage from test well data, consideration must also be given to the lateral and vertical flow of the local groundwater system. Where shallow watertables are present (< 2 m) water moving below the root zone usually results in a rise in the watertable within 2 to 24 hours.

Even with drip irrigation, drainage can occur if it is managed poorly. Figure 7 shows the watertable response of a drip-irrigated vineyard (Cox, 1995). During this period of monitoring there was a watertable response to almost every irrigation. The watertable rises provide an estimate of 4 to 5 mm of drainage. This was measured directly below the vine row. Tensiometers in this position showed that there was free water at about 80 cm depth. However, 100 cm away from the emitter, into the inter-row area, it was much drier.

Figure 7 – Watertable measured directly under drip emitter

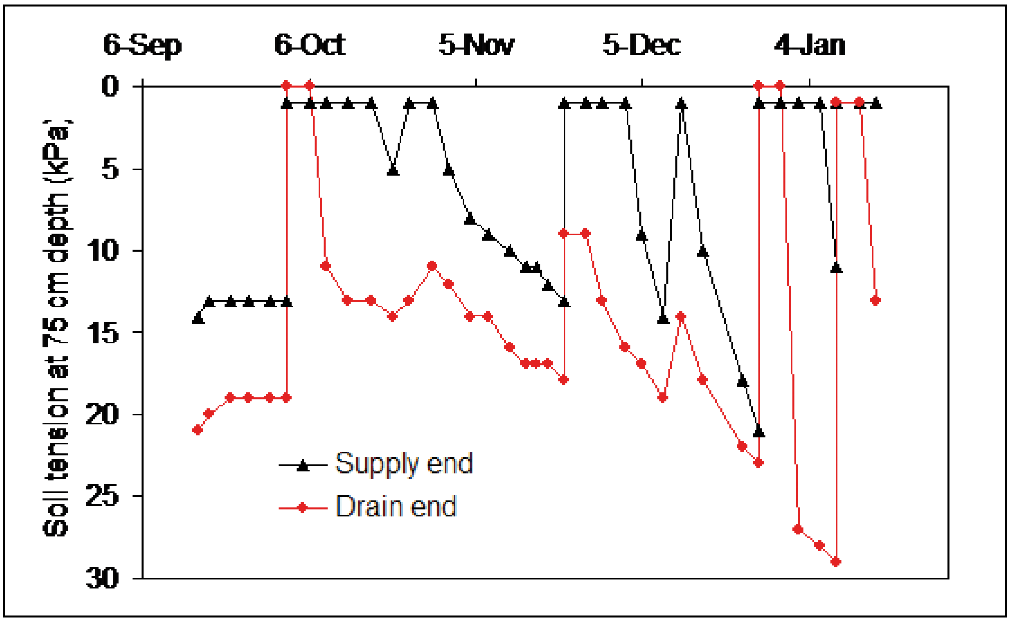


For tile drained locations, deep drainage can be monitored by recording the flow of water from the pump that lifts the water from the tile drain sump. In general, tile drains intercept a regional flow from the region (the base flow) and deep drainage from irrigation and rainfall on the drained area. The base flow and deep drainage flows are distinguished in the record by a separation in time scale. The base flow has a relatively long time scale and is correlated with regional irrigation practice and the presence of supply channels and drains while deep drainage has a short time scale and is highly correlated with local irrigation and rainfall. Deep drainage is given approximately as the volumetric flow rate of the pump divided by the irrigated area. To obtain an accurate estimate of deep drainage the groundwater flow system must again be considered.

When watertables are deep, test wells are not useful for monitoring deep drainage because there is a long lag time and reduced response between the irrigation event and watertable movement. In this case a soil moisture sensor placed beneath the root system is most useful. Soil moisture sensors either measure volumetric water content or soil water potential, and both types are able to monitor deep drainage. However, soil water potential (or soil tension) devices are superior because they are more sensitive to small changes in deep drainage. In general, a rapidly draining soil has a soil water potential greater than –10 kPa. To monitor deep drainage, tensiometers are installed beneath the root zone.

Figure 8 shows a record of the soil water potential at a depth of 75 cm beneath a furrow-irrigated soil. Periods of deep drainage follow immediately after irrigation and waterlogging occurs for a few days.

Figure 8 – Soil water potential at 75 cm, furrow irrigation



To estimate deep drainage from tensiometer data a pair of tensiometers are spaced apart vertically and the hydraulic gradient is measured. This gradient is then multiplied by the soil hydraulic conductivity at the location of the tensiometers.

REDUCING DEEP DRAINAGE

Deep drainage is likely to occur due to poorly developed root systems and low evaporative demand. Drainage throughout the season can occur if irrigations are too large or too frequent.

Irrigation method plays a major role in deep drainage. Deep drainage is reduced when flood and furrow irrigation layout is improved by reducing row length, changing furrow shape and increasing flow rate. Drip irrigation reduces the risk of deep drainage because small volumes of water can be applied so that small moisture deficits can be managed. However, drip irrigation is still found to have deep drainage because the ability of the soil to move water horizontally maybe overestimated by the irrigation designer and irrigator.

APPENDIX: WATER USE EFFICIENCY AND PRODUCTIVITY FRAMEWORKS IN ASSESSING RETURNS FOR IRRIGATION WATER IN THE AUSTRALIAN VEGETABLE INDUSTRY

Nihal Jayawardane and Evan Christen, CSIRO Land and Water & CRC Irrigation Futures

Water use efficiency and productivity (WUEP) frameworks can be used to accurately quantify the efficiency and productivity of irrigation water in vegetable cropping under current farming and irrigation practices. They could also be used to predict potential changes in water use efficiencies for improved irrigation practices, and to quantitatively monitor WUEP changes with on-field introduction of these improved practices. Combining these irrigation efficiency and productivity values with economic parameters can provide estimates of the economic returns to irrigation water use on vegetable farms under different irrigation management practices, for comparison with other competitive uses of water. The WUEP data could be used to determine the effectiveness of irrigation management practices to meet the specific agronomic needs of different vegetable crops on farms.

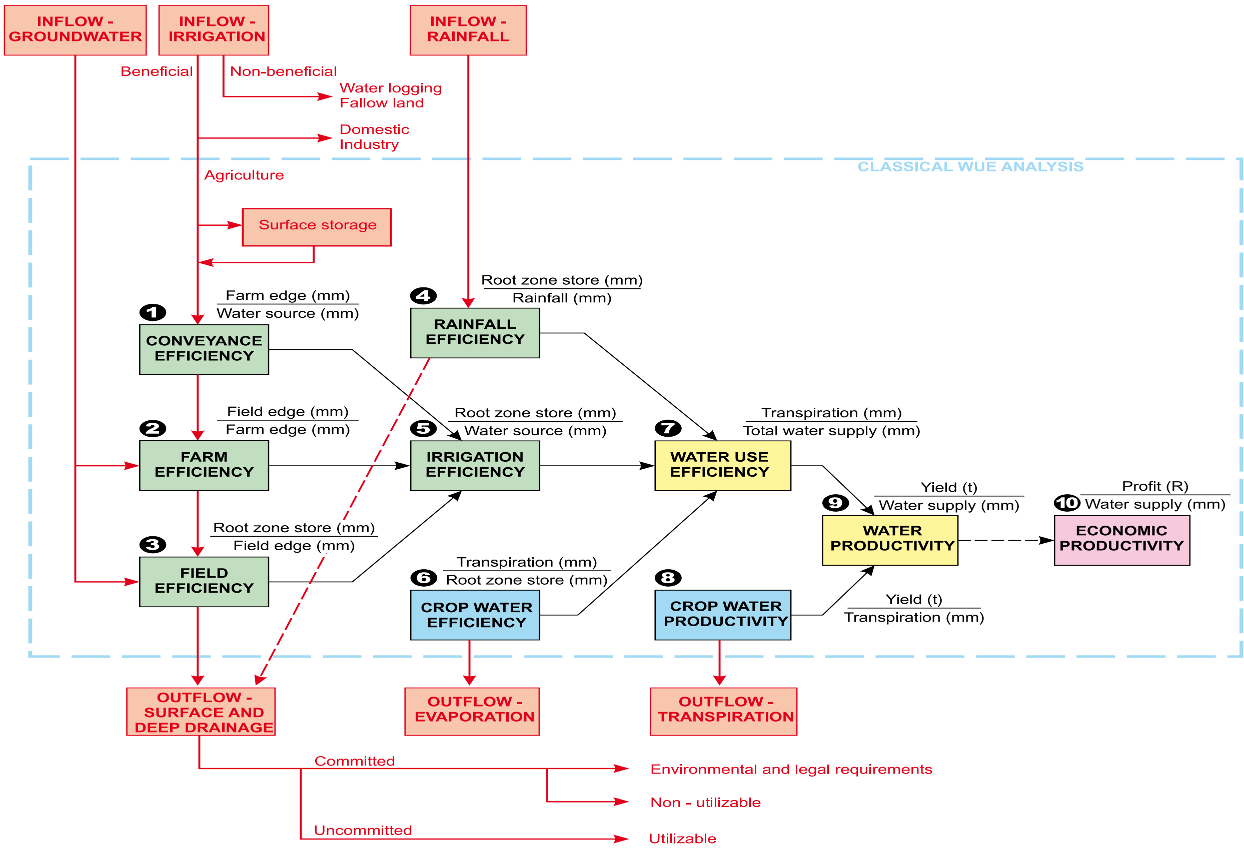
1. WATER USE EFFICIENCY AND PRODUCTIVITY FRAMEWORKS

The term ‘water use efficiency and productivity’ (WUEP) has been used with various engineering and agronomic connotations and definitions. Previous studies have led to a ‘classical’ approach for defining agricultural WUEP parameters as the ratio of outputs to inputs at each step in the irrigation water transport and transformation processes to plant products (Smith 2000, Schmidt 2001). This approach provides a detailed interactive scientific framework to directly link with on-going paddock-scale research on increasing both water use efficiency and water productivity by modifying soil, agronomy and irrigation practices.

An alternate approach that involves using simple water accounting procedures (Molden 1997, Molden et al. 2003) at different field scales has also been proposed. This approach is especially useful in quantifying the effects of other relevant hydrological management aspects at the larger catchment scales, such as water reuse and water quality changes, and in distinguishing real water savings from paper water savings.

Figure A1 shows an integrated framework incorporating the water accounting procedures (shown as red boxes) into the classical approach (shown within the blue outline box) developed by Smith (2000). In the classical approach, the WUEP parameter **irrigation efficiency** combines conveyance, farm and field efficiencies. This is a measure of how efficiently water is delivered to the root zone for potential plant use. Similarly, **rainfall efficiency** is the fraction of rain that infiltrates into the soil and is stored in the rootzone for subsequent uptake by crops. Factors such as the irrigation systems, crop type, soil type and agronomic management affect the system’s ability to store water in the soil root zone for potential use by crops, by reducing water losses that occur through deep percolation and excess run-off. Not all water that is stored in the soil root zone is transpired by the crop. Some of the water stored is lost by direct soil evaporation, not providing a production benefit. The fraction of water stored in the root zone that is used for crop transpiration is termed **crop water efficiency.**

Figure A1 – Integrated framework for WUEP assessment



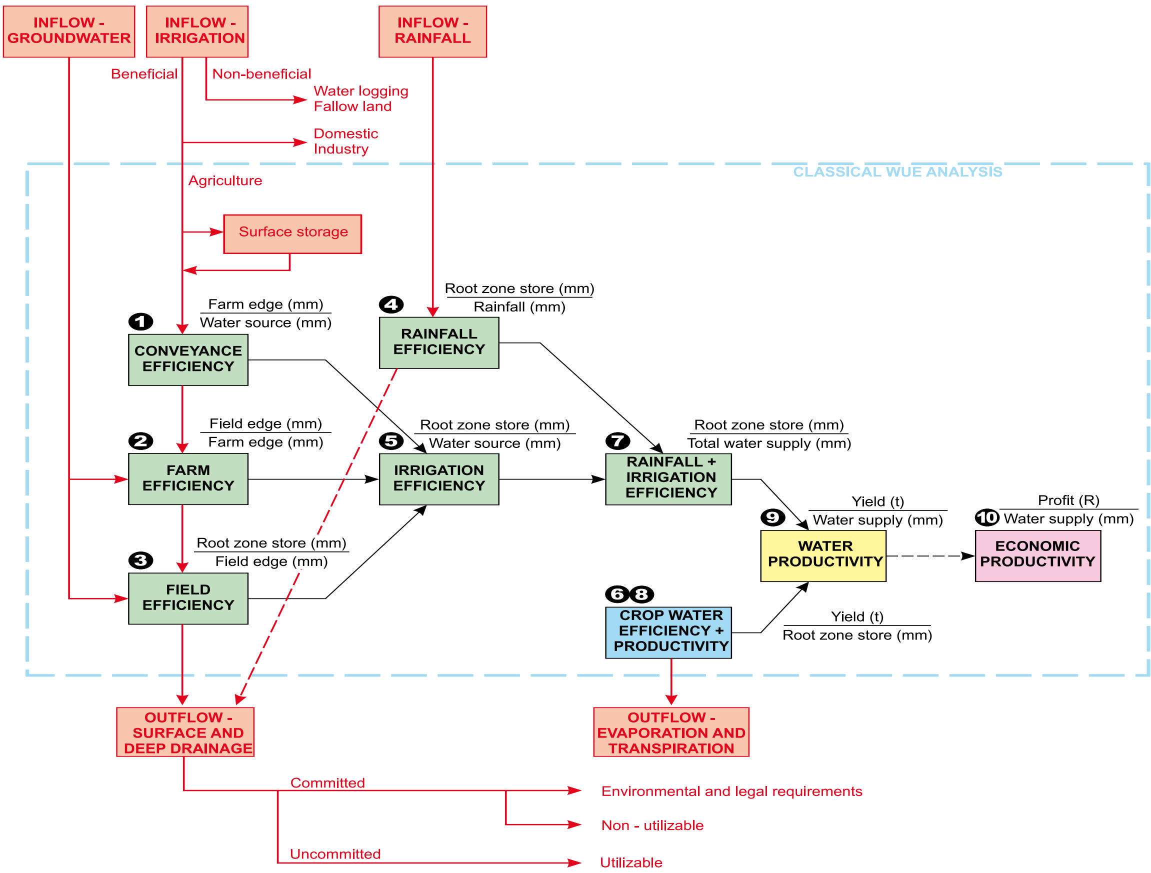
Overall **water use efficiency** is determined by combining the rainfall, irrigation and crop water efficiencies. Crops transpire at all stages of growth and by necessity have to develop a full plant structure in order to produce the saleable product of interest to the farmer e.g. grain, fibre and fruit. Crop production involves factors influencing the process of conversion of water into carbohydrates and crop biomass and ultimately saleable yield.

The ratio of saleable yield to transpiration is called **crop water productivity**. This is influenced by factors such as the crop type, water and fertiliser management, crop health, climatic conditions and soil type.

Water productivity is the combined product of **water use efficiency** and **crop water productivity**. Combining these irrigation efficiency and productivity values with economic parameters can provide estimates of the economic returns to irrigation water.

In field applications, it is often not possible to accurately analyse **irrigation efficiency** and **rainfall efficiency** separately from available field data. Therefore, in the modified WUEP framework (Figure A2) these two terms were combined into **rainfall + irrigation efficiency**. This is not a disadvantage, as making better use of rainfall is important for increasing irrigation efficiency. In the modified framework we also combine soil evaporation and crop transpiration, which are much easier to measure or estimate as total crop evapotranspiration in the field, and we use this combined value in defining the modified WUEP parameter **crop water efficiency + productivity**.

Figure A2 – Modified framework for WUEP asessment



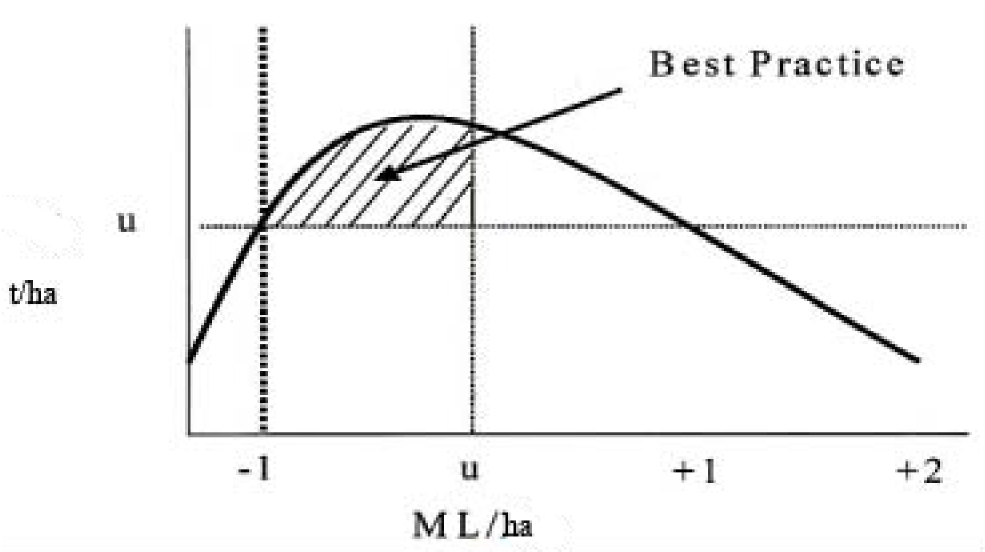
Any water escaping beyond the crop root zone contributes to the deep drainage flows (Figures A1 and A2) into groundwaters, which could then flow laterally out of the farm paddock areas. Such lateral water flows moving into farming areas with shallow groundwater table areas could directly contribute to crop uptake by capillary 'groundwater inflow' (Figures A1 and A2). Groundwater pumping from deep watertables can also contribute to 'inflow irrigation' (Figures A1 and A2), by supplementing surface irrigation supplies.

Where data is available on vegetable farms, the WUEP parameters can be calculated to provide quantitative assessment of irrigation performance in Australian vegetable cropping industries under different irrigation designs and management practices.

2. SIMPLIFIED ANALYSIS APPROACHES TO EVALUATE BEST IRRIGATION MANAGEMENT PRACTICES FOR VEGETABLE CROPS

The WUEP analysis requires the collection of specific water balance data from vegetable farms, which may not be available in many farm surveys. The more basic data sets collected in many farm surveys can be used in simplified analysis procedures to evaluate the extent of adoption of best irrigation management practices. For instance, farm surveys on irrigation efficiency practices often collect basic data on crop yield per hectare and water usage in megalitres per hectare for specific vegetable crops. This information can be graphed to yield a data scatter, which is commonly represented by the curve shape in Figure A3.

Figure A3 – Determination of best irrigation management practices from farm survey information



The average values of yield and water usage per hectare on individual farms plotted on this graph (Figure A 3) can be analysed to assess the use of best irrigation and agronomic practices, as follows. The top left-hand sector represents farms that yield above average yields with use of below-average water applications, possibly indicating the use of best irrigation management practices. The bottom left indicates farms that need to focus on increasing yields and the top right sector indicates farms that need to focus on reducing water usage. The bottom sector represents farms that need to adopt measures to both increase yields and reduce water usage. The coordinates in the graph could be converted to economic parameters such as economic returns per hectare or water costs per hectare to aid in economic analysis of irrigation practices.

3. FIELD TRIAL INFORMATION ON BEST IRRIGATION MANAGEMENT PRACTICES FOR VEGETABLE CROPS IN OVERSEAS COUNTRIES AND AUSTRALIA

Optimising vegetable irrigation practices requires an understanding of the water requirements of vegetable crops at different growth stages so that they can be adequately met by irrigation applications. This information could be obtained from previous field experimentation. Such background information could be useful in analyzing WUEP data from field studies.

The following information on best management for vegetable crop irrigation is based on extracts from Sanders (1997) and Queensland DPI publication series on 'Water for Profit'.

3.1 Vegetable crop irrigation experience in USA

The following information was extracted from Sanders (1997) on vegetable irrigation practices in California, USA.

Vegetables are 80 to 95 percent water. Because they contain so much water, their yield and quality suffer very quickly from drought. When vegetables are sold, a 'sack of water' with a small amount of flavoring and some vitamins is being sold. Thus, for good yields and high quality, irrigation is essential to the production of most vegetables. If water shortages occur early in the crop's development, maturity may be delayed and yields are often reduced. If a moisture shortage occurs later in the growing season, quality is often reduced even though total yields are not affected. Most vegetables are rather shallow rooted and even short periods of two to three days of stress can hurt marketable yield. Irrigation is likely to increase size and weight of individual fruit and to prevent defects such as toughness, strong flavor, poor tipfill and podfill, cracking, blossom-end rot and misshapen fruit. On the other hand, it reduces soluble solids in muskmelons and capsaicin in hot peppers if applied during fruit development.

Growers often wait too long to begin irrigating, thinking, 'It will rain tomorrow'. This often results in severe stress for the portion of the field that dries out first or receives irrigation last. Another common problem is trying to stretch the acreage that can reasonably be covered by available equipment. Both of these practices result in part or all of the field being in water stress. It is better for a good job be done on some of the acreage rather than a 'half-way job' being done on all the acreage.

Drought stress can begin in as little as three days after a 35 mm rain or irrigation in such crops as tomatoes in light soils. Thus, frequent irrigation is necessary for maximum yield. Soil moisture requirements differ with the crop and stage of crop development. Soil moisture availability varies with the amount of water in the soil and the type of soil. Soil type is very important in planning for and using an irrigation system. Various vegetable crops are listed in Table 1 as to the critical stage and irrigation needs.

Droplet size and irrigation rate are also very important in vegetable crops. Large droplets resulting from low pressure at the sprinkler head can cause damage to young vegetable plants and contribute to crusting when soil dries. Irrigation rate is also important in sandy soils that absorb water more readily than clay soils. However, clay soils have a greater percent of the water available. Irrigation rate will depend on soil type but application rates should not exceed about 10 mm per hour for sandy soils, about 7 mm per hour for loamy soils or about 5 mm per hour for clay soils. High application rates will result in irrigation water running off the field, contributing to erosion and fertiliser run-off.

Improving stands – Most vegetables have small seeds which are planted 20 mm deep or less. When seeds are planted shallow, the upper layer of soil can dry rapidly, leaving the seed half-germinated, with not enough soil moisture to complete germination. When this happens, no stand or at best an incomplete stand will result. An irrigation of 12 to 20 mm immediately after planting should be applied to settle the soil and to start seeds germinating. For larger seeded crops, irrigation a few days prior to seeding is desired. If seeds are slow to come up due to cool temperatures or slow germination, then irrigations of about 25 mm should be applied as needed. This should be done to keep the area around the seed moist until seedlings emerge. Irrigation is a valuable tool in getting a good, uniform stand which ensure high yields. Good uniform stands also mean uniform harvest dates and more efficiency of production.

Vegetable transplants also require good soil moisture. A light irrigation of about 20 mm will help establishment by providing a ready supply of water to young broken roots.

Irrigation at planting time can also reduce soil crusting and hasten seedling emergence. If 12 to 20 mm of irrigation is slowly applied, either with low rates or by turning the irrigation system off long enough to allow water to soak in, crusting can be reduced and the stand will be improved.

Product development and fruit set - Wide fluctuations in soil moisture injure the fruit crops of vegetables like tomatoes and peppers (Tables A1 and A2). These fruits contain large amounts of water and depend on this water for expansion and growth. When soil moisture is allowed to drop below the correct level, the fruit does not expand to its maximum possible size before it ripens, thus reducing yield. If moisture is allowed to fluctuate too much, blossom end rot can occur, and the fruit will no longer be useable.

If moisture fluctuation occurs during the fruit expansion stage, fruit cracking will occur. Fruit cracking usually occurs when inadequate water has been applied and then heavy rains bring too much water (Tables A1 and A2). The best way to prevent fruit cracking is a steady moisture supply. Second growth or knobs in potatoes are also caused by soil moisture fluctuations.

Rooting depth – It is important that the soil profile be filled with water at each irrigation. Frequent light irrigations result in shallow root systems. Shallow root systems result in plants being stressed even in short periods of water deficit. See Table A1 for crop-specific information. On the other hand, excessive irrigation leaves crops vulnerable to leaching from rain or irrigation.

The rooting depth of various vegetables is listed in Table A2. It is important that shallow-rooted crops receive more frequent irrigations.

Preferred minimum soil moisture – Soil moisture is measured with a **tensiometer** or **soil block**. A tensiometer is preferred for sandy soils and soil blocks preferred for clays and loams. Tensiometers report soil moisture in centibars (.001 bar). Suggested soil tensions for various vegetables are reported in Table A1. Soil blocks report available soil moisture (ASM).

Amount and timing – Irrigation amounts and time between irrigations are critical to efficient irrigation practices. Some suggestions for amount and timing of irrigations are presented in Table A3.

Critical moisture periods – Critical periods of irrigation needs can best be defined as that time when soil moisture stress can most reduce yield in an otherwise healthy crop (Table A1). This is not to say that it is the only time in the life of the crop that moisture stress reduces yield. It is, however, the time when stress has the greatest effect.

Irrigation method – Vegetable crops differ in which method of irrigation can be used economically in their production.

Drought tolerance – Drought tolerance is an indication of a crops ability to withstand short periods of drought without significantly reducing yield. We have classified vegetables for drought tolerance in Table A2.

Defects from stress – Most vegetables respond to water deficit with reduced yield and quality. However, most crops also express this stress with growth abnormalities: these are listed in Table A2.

Table A1 – Vegetable critical moisture periods, drought tolerance, rooting depth, and concerns (Sanders 1997)

Crop	Maximum soil tension (Bars)	Irrigation critical moisture period
Asparagus	-.70	Crown set and transplanting
Beans, lima	-.45	Flowering
Beans, pole	-.34	Flowering
Beans, snap	-.45	Flowering
Beans, soy (edible)	-.70	Flowering
Beet	-2.00	Root expansion
Broccoli	-.25	Head development
Brussels sprout	-.25	Sprout formation
Cabbage	-.34	Head development
Carrot	-.45	Seed germination, root expansion
Cantaloupe	-.34	Flowering and fruit development
Cauliflower	-.34	Head development
Celery	-.25	Continuous
Chinese cabbage	-.25	Continuous
Collards	-.45	Continuous
Corn, sweet	-.45	Silking
Cucumber, pickles	-.45	Flowering and fruiting
Cucumber, slicer	-.45	Flowering and fruiting
Eggplant	-.45	Flowering and fruiting
Greens (turnip, mustard, kale)	-.25	Continuous
Leek	-.25	Continuous
Lettuce (head, Bibb, leaf, cos)	-.34	Head expansion
New Zealand Spinach	-.25	Continuous
Okra	-.70	Flowering
Onion	-.25	Bulbing and bulb expansion
Parsnip	-.70	Root expansion
Peas, green	-.70	Flowering
Peas, Southern	-.70	Flowering and pod swelling
Peppers	-.45	Transplanting flower up to 1/2′ fruit

Crop	Maximum soil tension (Bars)	Irrigation critical moisture period
Potato, Irish	-.35	After flowering
Pumpkin	-.70	Fruiting
Radish	-.25	Continuous
Rhubarb	-2.00	Leaf emergence
Rutabagas	-.45	Root expansion
Squash, summer	-.25	Fruit sizing
Squash, winter	-.70	Fruit sizing
Sweetpotato	-2.00	Fruit and last 40 days
Tomato, staked	-.45	Fruit expansion
Tomato, ground	-.45	Fruit expansion
Tomato, processing	-.45	Fruit expansion
Turnip	-.45	Root expansion
Watermelon	-2.00	Fruit expansion

Table A2 – Vegetable drought tolerance, rooting depth, and concerns (Sanders 1997)

Crop	Drought tolerance[1]	Rooting depth[2]	Defects caused by water deficit	Comments
Asparagus	H	D	Shriveling	Will withstand most drought
Beans, dry	M	M	Poor pod fill & small beans	No irrigation after pods begin to dry
Beans, lima	L-M	D	Poor pod fill & small beans	Cooling irrigation can increase yield
Beans, pole	L-M	M	Poor pod fill & pithy pods	Steady moisture supply is necessary during flowering
Beans, snap	L-M	M	Poor pod fill & pithy pod	Irrigation prior to flowering not as critical
Beans, soy (edible)	M	M	Poor pod fill	Irrigation prior to flowering not as critical
Beet	M	M	Growth cracks	
Broccoli	L	S	Strong flavor	
Brussels sprout	M	S	Poor sprout production	
Cabbage	M-H	S	Growth cracks	
Carrot	M-H	S-M	Growth cracks, misshapen roots	Avoid droughts during root expansion
Cantaloupe	M	S-M		
Cauliflower	L	S	Ricey curd, buttoning	
Celery	L	S	Small petioles	Moisture deficit can stop growth irreversibly
Chinese cabbage	L	S	Tough leaves	
Collards	M	S	Tough leaves	
Corn, sweet	M-H	S	Poor ear fill	Irrigation prior to silking has little value
Cucumber, pickles	L	S-M	Pointed & cracked fruit	Moisture deficit can drastically reduce yield and quality
Cucumber, slicer	L	S-M	Pointed & cracked fruit	Moisture deficit can drastically reduce yield and quality
Eggplant	M	M	Blossom-end rot, misshapen fruit	
Greens (turnip, mustard, kale)	L	M	Tough leaves	Good continuous moisture essential to good yields
Leek	L-M	S	Thin scale formation	
Lettuce (head, Bibb, leaf, cos)	M-H	D	Tough small leaves	

Crop	Drought tolerance[1]	Rooting depth[2]	Defects caused by water deficit	Comments
New Zealand Spinach	L	S	Tough leaves, poor production	Irrigate to keep growth continuous and rapid
Okra	M-H	D	Tough pods	Irrigation can reduce yield
Onion	L	S	Poor size	
Parsnip	H	D		
Peas, green	L	M	Poor pod fill	
Peas, Southern	M	M	Poor pod fill	Plants will recover from drought but yield is reduced
Peppers	M	M	Shriveled pods, blossom-end rot	Irrigate for increased pod size and yield
Potato, Irish	M	S	Second growth & misshapen roots	Irrigate only during extreme drought during root development
Pumpkin	M	D	Blossom-end rot	
Radish	L	S	Pithy roots	Keep soil moisture levels high to promote rapid growth
Rhubarb	M	D	Pithy stems	
Rutabagas	M	M	Tough roots	
Squash, summer	L	M	Pointed & misshapen fruit	Fruit sizing. Irrigation can double or triple yields
Squash, winter	M	D		
Sweetpotato	H	D	Small & misshapen roots	
Tomato, trellis	M	D	Blossom & root growth cracks	Continuous water supply helps avoid blossom-end rot and increase fruit size
Tomato, ground	M	D	Blossom & root growth cracks	Continuous water supply helps avoid blossom-end rot and increase fruit size
Tomato, processing	M	D	Blossom & root growth cracks	Continuous water supply helps avoid blossom-end rot and increase fruit size
Turnip	M	M	Woody roots	
Watermelon	MH	D	Blossom end rot	This crop can withstand extreme drought, but there will be some yield reduction

1 Drought tolerance: L = low; M = moderate; H = high.
2 Depth of rooting, of most roots: S = shallow, 300–450 mm; M = moderate, 450–600 mm; D = deep, 600 mm plus (note also depends upon soil type and irrigation practice)

3.2 Information from QDPI&F 'Water for Profit' factsheets

The following information was extracted from the 'Water for Profit' factsheets, produced by QDPI&F.

Table A3 – Optimum conditions for vegetable yield (QPI 'Water for Profit' factsheets)

Crop	Soil depth of 80% moisture extraction	Water required ML/ha	Maximum soil suction for irrigation kPa	Potential yield (t/ha)	Comments*
Beetroot	30	2.5–3.5	40–50	30–40	Over-irrigation can cause disease Adequate soil moisture needed during plant establishment
Brassica (Brocolli, Cauliflower)	35	2.4–4.0	Broccoli 30–40 at 15 cm Cauliflower 40–60 at 15 cm	Broccoli 7–8 Cauliflower 40	Over-irrigation can cause disease Under-irrigation leads to tip burn
Capcicum	30	2.5–3.0	30–40 at 20 cm (earlier at flowering and early fruit fill)	24–36	
Lettuce	20	2.3	15–20 at 15 cm in warm weather	30–50	
Melons	40	2.5–3.0	30–40 at 25 cm	40–50	Encourage root development in early stages
Onions	50	3–5	30–45 at 15 cm	60–70	Encourage root development in early stages
Sweet potatoes	30	2.5–3.0	40–60 at 25 cm (irrigate at 30–40 at tuber initiation)	35–50	
Tomatoes	40	4–6	30–40 at 25 cm (irrigate at 25–35 at fruitfill)	60–90	
Watermelons	40	2.5–3	30–40 at 25 cm	60–70	
Zucchini, Squash	25	1.6–1.8	30 at 20 cm (lower values during fruit fill)	20–25	

General comments: Efficient crop water use and high yield potentials can only be achieved if other agronomic factors such as nutrition, disease and pest management are optimised.

4. APPLICATION OF THE WUEP FRAMEWORK TO IRRIGATION SCHEMES

4.1 Existing information from MIA

Detailed farm surveys on irrigation water usage on field crops have been carried out in the Murrumbidgee Irrigation Area, but there are no data for vegetable crops which are often grown in rotation with field crops. This farm survey information was used to evaluate rainfall + irrigation efficiency on the irrigation farms (Jayawardane et al. 2004), as a measure of the percentage of water applied which is retained within the rooting depth of the crops for crop evapotranspiration. The data was also used to calculate water productivities for specific crops.

These values of rainfall + irrigation efficiency for field crops (Table A4) could also be generally applicable to vegetable crops which are grown in rotation on the MIA farms. The value of around 0.7 possibly reflects an average value for the range of irrigation layout systems ranging from contour irrigation to border check and permanent bed farming systems.

Rahman and Darnley-Naylor (1994a, 1994b) estimated that around 85% of the MIA irrigation area is under contour layout in which the rainfall + irrigation efficiency under poor irrigation management was around 0.5. They discussed in detail the measures that could be used to increase water use efficiency on these lands by changing to border check and permanent bed farming systems as well as by improving the on-farm irrigation management procedures, including reuse of drainage water.

Table A4 – Mean water use efficiencies and productivities for specific crops, from the WUEIS survey data, 1997 to 2003

	Rainfall + irrigation efficiency	Crop water efficiency + productivity (kg/ha/mm)	Water productivity (kg/ha/mm)	Crop water productivity (kg/ha/mm)
Summer crops				
Rice	0.86	8.12	6.99	8.86
Maize	0.75	8.98	6.84	10.07
Corn	0.70	12.04	7.87	11.61
Corn silage	0.69	5.31	3.67	5.54
Soybean	0.70	3.65	2.50	3.74
Mean	0.74	7.62	5.58	7.97
Winter crops				
Wheat	0.69	12.41	8.48	12.57
Oats	0.72	8.87	6.39	9.79
Barley	0.70	12.46	8.61	13.08
Canola	0.70	4.67	3.28	4.71
Faba bean	0.65	8.76	5.72	8.56
Mean	0.69	9.43	6.50	9.74
Perennial crops				
Lucerne	0.77	16.71	12.69	17.53

Potentially the use of improved irrigation layout design and irrigation management could be expected to increase the value of irrigation efficiency in contour systems from around 0.5 to more than 0.8, while in border check and permanent bed farming systems it could be increased from around 0.7 to more than 0.9 (Rahman and Darnley-Naylor 1994a, Merriam and Keller 1978). The potential for whole-of-system water savings by farmers adopting improved irrigation layout and management could be quantified by combining detailed farm surveys information on currently existing irrigation systems and practices, with assessments of current on-farm irrigation and rainfall efficiencies. An understanding of the barriers to adoption of improved irrigation systems and management is also required.

The adaptability of drip and sprinkler irrigation to broadacre cropping which could potentially further increase water use efficiency and productivity has not been previously assessed in field studies on the clayey soils in the area. Specific information on crop water efficiency + productivity for vegetable crops needs to be obtained from future surveys from vegetable farming paddocks.

4.2 New analysis

The data currently being collected in new surveys of water usage in the vegetable growing areas could be used for analysis through the WUEP framework.

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