Managing Water for Yield and Profit

A training guide for Irrigators in the Australian Vegetable Industry

CONTENTS

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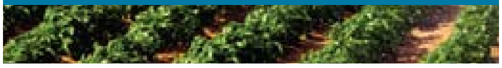


Overview

1. Overview

This booklet is a summary of the key messages from the AHR Training workshop “Managing Water for Yield and Profit”. The workshop and the material in this guide are based on data that AHR have collected from on-farm research and trials over the past five years. This data has been collected from “real” situations and “real” farms.

AHR used soil moisture probes to collect field data during the on-farm trials for a wide range of horticultural crops such as seedless watermelon, rockmelon, grapes, lettuce, baby leaf salad vegetables, broccoli, carrots and potatoes.

The research was conducted in Robinvale, Bowen, Douglas Daly, Mataranka, Lockyer valley, Bairnsdale, Kununurra, Camden, Condobolin, Toowoomba and Richmond, representing a wide range of regions in several states of Australia.

The data collected also includes information on water use using different irrigation methods such as overhead sprinklers, drip irrigation and buried trickle.

AHR Training is aware of the information overload on water use and soil moisture monitoring. This booklet and the associated workshop have been designed with this in mind and have tried to ensure that they will facilitate access to appropriate resources and information for vegetable growers. However, it is important to use and adapt this information to maximise yield and quality for individual regions and farms.

2. Introduction

Introduction

Key Messages

- Water use efficiency is a critical issue for yield and profit in the vegetable industry.
- To demonstrate relative efficiencies for water use it is essential that growers measure the amount of water applied.
- More accurate on-farm data in relation to water use will help set benchmarks and to demonstrate to the wider community the already efficient water use practices of the vegetable industry.

Of all the inputs that drive the vegetable industry, adequate quantities of good quality water for irrigating crops is one of the most critical issues the industry currently faces.

The objective of this booklet and associated workshop is to provide an understanding of the tools required and the opportunities available to improve the efficiency and profitability of water use in vegetable crop production. Data will be presented to show how optimum water use increases the yield and quality of vegetable crops. With too much or too little water the yield and quality of any crop is compromised.

To make things even more complicated, Government and regulatory pressure to improve irrigation water use efficiency is increasing. The hope is that increasing the efficiency, or reducing wasteful water use, will make more water available for productive use or to meet environmental needs.

For the vegetable industry there are currently two related issues in regard to irrigation water use, and these are presented in order of importance;

1. Managing water to ensure maximum yield and quality; and
2. Meeting the Government and community expectations for efficient water use. For this priority it is not that the vegetable industry is inefficient, there is just not enough data to demonstrate the relative efficient water use of the industry.

Quantifying water use efficiency on-farm

Water use efficiency is a generic term that covers a range of performance indicators irrigators can use to monitor the performance of their irrigation practices based on production or net profit.

There are two key indicators of how well growers use water. The first is crop production per ML of water used and is called the ***Irrigation water use index***. The second is how much profit can be made from each ML of water and this is called the ***Operating profit water use index.***

These two important measures of water use efficiency can be calculated as follows and help growers quantify how changes in water management can impact on a business' bottom line.

Irrigation water use index (IWUI) =

$$\frac{\textit{Total production for farm (tonnes)}}{\textit{Total water used on farm (ML)}}$$

Operating profit water use index (OPWUI) *=*

$$\frac{\textit{Gross return (\$) - Variable costs (\$) – Overhead Costs (\$)}}{\textit{Total water used on farm (ML)}}$$

In the example, the figures are expressed on a whole farm basis, but could equally well be expressed per cropping unit or per hectare.

How does horticulture compare to other rural water users

The vegetable industry is the largest sector of the Australian Horticulture Industry and is virtually 100% irrigated.

In 2003/04 the vegetable industry accounted for just 4.6% of the total water used for irrigation (ABS Water Use on-farm 2003-04). The industry average water use is 4.1 ML per hectare, which is below the national average for agriculture which is 4.3 ML per hectare.

One of the problems facing the vegetable industry is the lack of actual water use data for many vegetable production enterprises. In a recent HAL Project Report, *VG04010 Maximising returns from water in the Australian Vegetable Industry* (Hickey *et al.*, 2006), it was stated that there is a need to conduct a detailed study of the threshold cost of water, beyond which vegetable growing becomes uneconomic.

Information such as what is the maximum threshold that can be paid for water before it becomes unfeasible to grow vegetables is relatively unknown. This is particularly important where limited sources of water are driving higher land and water prices. Growers need real district information in order to make good production decisions in difficult times.

It is impossible for individual growers or the industry as a whole to know their water use efficiency relative to other industries if 'real' data is not available. It is essential that growers know what they are using so that they can demonstrate, with hard facts, their current water use efficiency and the improvements they can or have made.

How can water use efficiency be improved?

Recent drought and an increased demand for water across many of the growing regions in Australia have made the vegetable industry well aware of the need for highly efficient irrigation systems in order to produce high yielding, quality crops in dry seasons.

Growers are adopting more efficient systems including sub surface drip irrigation and computer controlled overhead sprinklers or soil moisture monitoring equipment. These techniques ensure high yields are produced as water is supplied when and where it is needed.

This booklet and associated workshop aims to provide information and tools to help growers manage crop water use for maximum returns, minimise production risks and calculate the real value of the water applied.

3. Why Plants Need Water

Key Messages

- Managing water use is about maximising plant growth. Too much or too little water will cause plant stress, which impacts directly on the physiology of the plant.
- The disrupted metabolism causes an increased risk of disease and also reduces the growth rate, yield and quality of the crop.
- Managing water is essential for managing profits.

Without water, life as we know it would not exist

Water fills a number of important roles in the physiology of the plant; roles which only water can play as a result of its unique physical and chemical properties.

1. **Thermal properties** – water is important for temperature regulation as it doesn't heat or cool too quickly, and cools plants by evaporating from the leaf surface.
2. **Solvent properties** – it carries nutrients and solutes required for growth.
3. **Biochemical reactions** – many of the biochemical reactions that are part of growth occur in water or water itself participates in the reactions, e.g:

Respiration energy for life

$$\underset{\text{glucose}}{C_6H_{12}O_6} + \underset{\text{oxygen}}{6O_2} \longrightarrow \underset{\text{carbon dioxide}}{6CO_2} + \underset{\text{water}}{6H_2O}$$

Photosynthesis - storing energy for respiration

$$\underset{\text{carbon dioxide}}{6\,CO_2} + \underset{\text{water}}{12\,H_2O} \xrightarrow{\substack{\text{Light energy}\\ \text{Chlorophyll}}} \underset{\text{glucose}}{C_6H_{12}O_6} + \underset{\text{oxygen}}{6O_2}$$

4. **Transparency** – allows sunlight to penetrate to power photosynthesis in the cells.

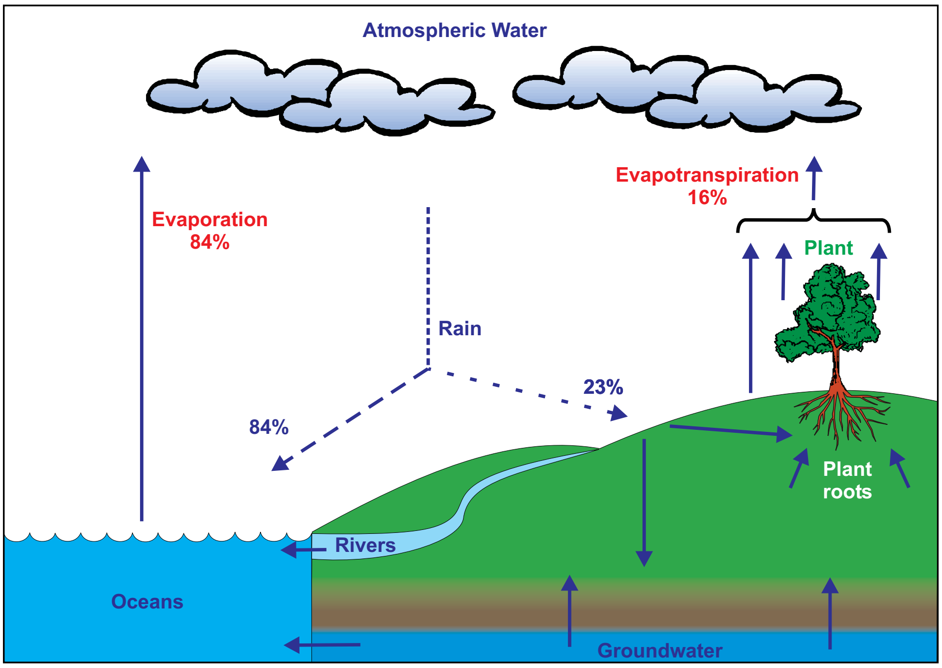


Figure 1. *Hydrological cycle.*

Without water, crops could not grow. Water is the most abundant constituent of most organisms. The simplified hydrological cycle (Figure 1) emphasises the connectedness of soil, plant and atmospheric water. This diagram highlights the complexities of determining irrigation water use and scheduling. Irrigators have many factors to consider when applying water including: soil type; evaporation rate; rainfall; and crop growth, if irrigation water is to be applied effectively and efficiently.

Water is essential for crop production. For example, water is required for the germination of seeds and as soon as growth starts water serves as a carrier in the distribution of mineral nutrients and plant food.

Plant cells grow by increasing in volume and for the cells to increase in volume they must take up water. If a cell can not take up water it will not grow.

In addition, all processes of metabolism require an aqueous environment in which to function. As a result, water forms 80% or more of an annual plant's substance and more than 50% of a woody species (Table 1).

Table 1. *Water proportion in some horticultural crops.*

Broccoli	91%	Cucumber	96%	Onion	90%
Cabbage	92%	Grape	81%	Spinach	92%
Carrot	88%	Kiwi fruit	83%	Tomato	94%
Celery	95%	Lettuce	96%		
Corn, Sweet Fresh	70%	Melon Cantaloupe	90%		

For maximum yield most crops need more water that what local rainfall provides

Seasonal evaporation from plant communities almost always exceeds rainfall, therefore supplementary water is needed to achieve a crop's capacity for yield. A combination of factors drives evaporation from a free water surface, namely solar radiation, wind speed, turbulence and humidity. In Australian agriculture (and especially in areas with predominantly winter rain), water deficits most commonly occur towards the end of the life cycle of annual crops, at a time when there is the largest impact on final crop yield.

The importance of available water in determining productivity cannot be underestimated. The rate of photosynthesis declines under conditions of water stress and, in cases of severe water stress, may cease completely (Figure 2).

Water movement in plants

Transpiration is the process that drives water movement through the plant from the roots to the atmosphere. Transpiration is driven by the loss of water from the plant, in the form of water vapour through the stomatal pores (90%) and the cuticle (10%). Nearly all water taken up is lost by transpiration and only a tiny fraction is used within the plant.

Importantly, the process of transpiration produces the energy gradient that largely controls the ascent of sap through the plant, which is beneficial because it cools the leaves and increases absorption of minerals. Research has shown that the leaves of plants not water stressed will be about 4°C cooler than the surrounding air temperature at solar noon. The plants use the principle of evaporative cooling where heat energy is drawn out of the plant to convert the water molecule from a liquid to a vapour. This loss of heat results in the tissue being cooled.

If the plant gets too hot, or the flow of water from the roots cannot match that lost through the stomates, then the plant will close the stomates and "shut down" in response to the water stress. This means photosynthesis and growth will stop. This results in a net reduction in plant yield. The application of irrigation water aims to prevent this situation.

The transpiration rate is influenced by the relative humidity of the surrounding air, air temperature and wind speed. If there is a breeze and the air is hot and dry then the transpiration rate is high.

Evaporation from the soil and transpiration from the plant occur simultaneously and there is no easy way of distinguishing between the two processes. The evaporation from soil is largely determined by the amount of solar radiation reaching the soil surface. This decreases as the crop develops and the crop canopy shades the ground area.

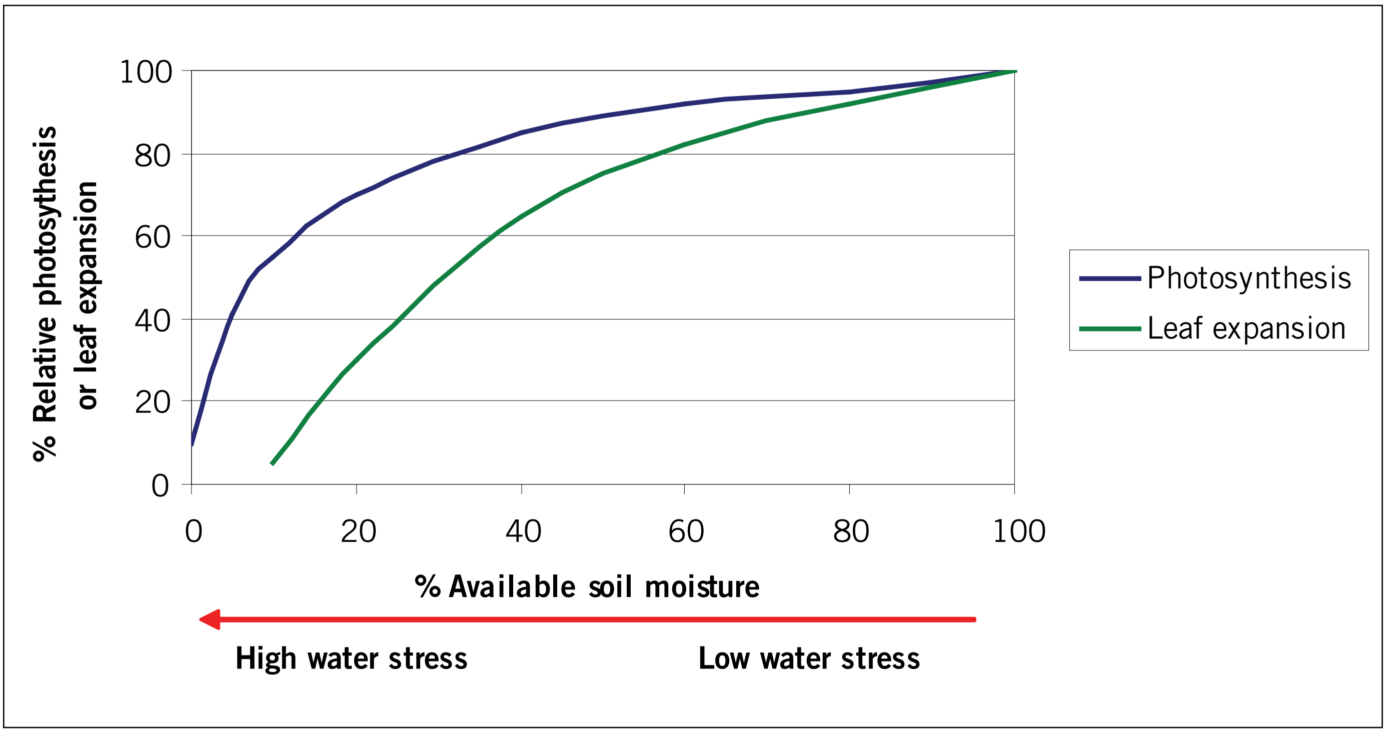
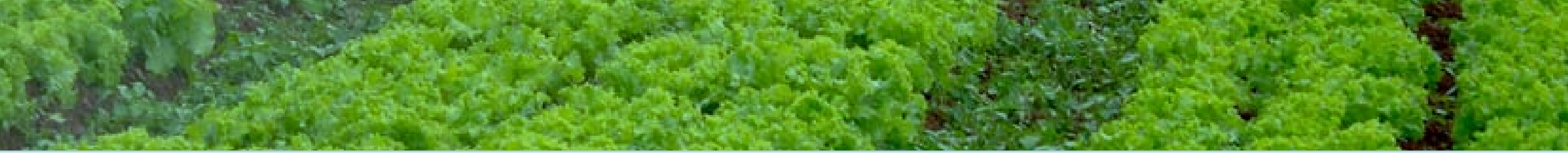


Figure 2. *Relationship between available water and relative net photosynthesis and relative leaf expansion. (Adapted from Roth et al., 2004)*



At sowing, nearly 100% of the evapotranspiration is from soil evaporation, while at full crop cover more than 90% of evapotranspiration is from plant transpiration (Figure 3).

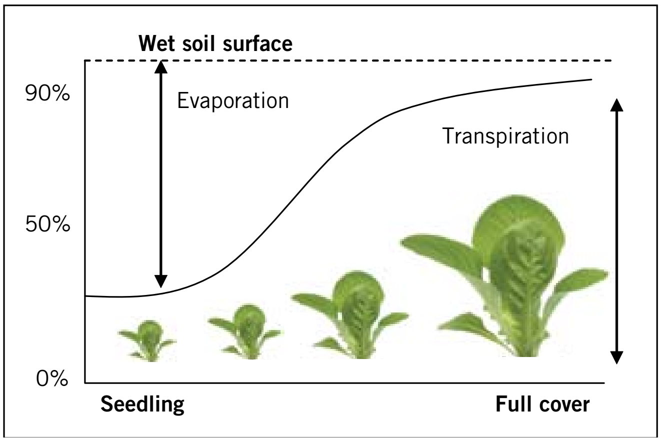


Figure 3. *The interaction between evaporation and transpiration on the evapotranspiration for a vegetable crop. The curve is when the soil surface is kept dry but the crop receives sufficient water to sustain full transpiration.*

As the crop develops, the ground cover, crop height and leaf area change. For most crops the growing period can be divided into four distinct growth stages; initial, crop development, mid-season and late season/maturity (Figure 4). The water use at these times changes. There are several ways to estimate what the water use will be for a crop over time. The crop water use can be calculated using either a crop factor or a crop coefficient. These two factors are similar and equally valid, but they are not the same. The following examples show when a crop factor is used and when a crop coefficient is used.

*Crop water use (mm) = **Crop Factor (K_f)** x Pan Evaporation (E_{pan})*

The crop factor relates the evapotranspiration from a plant to the rate of evaporation from an open pan.

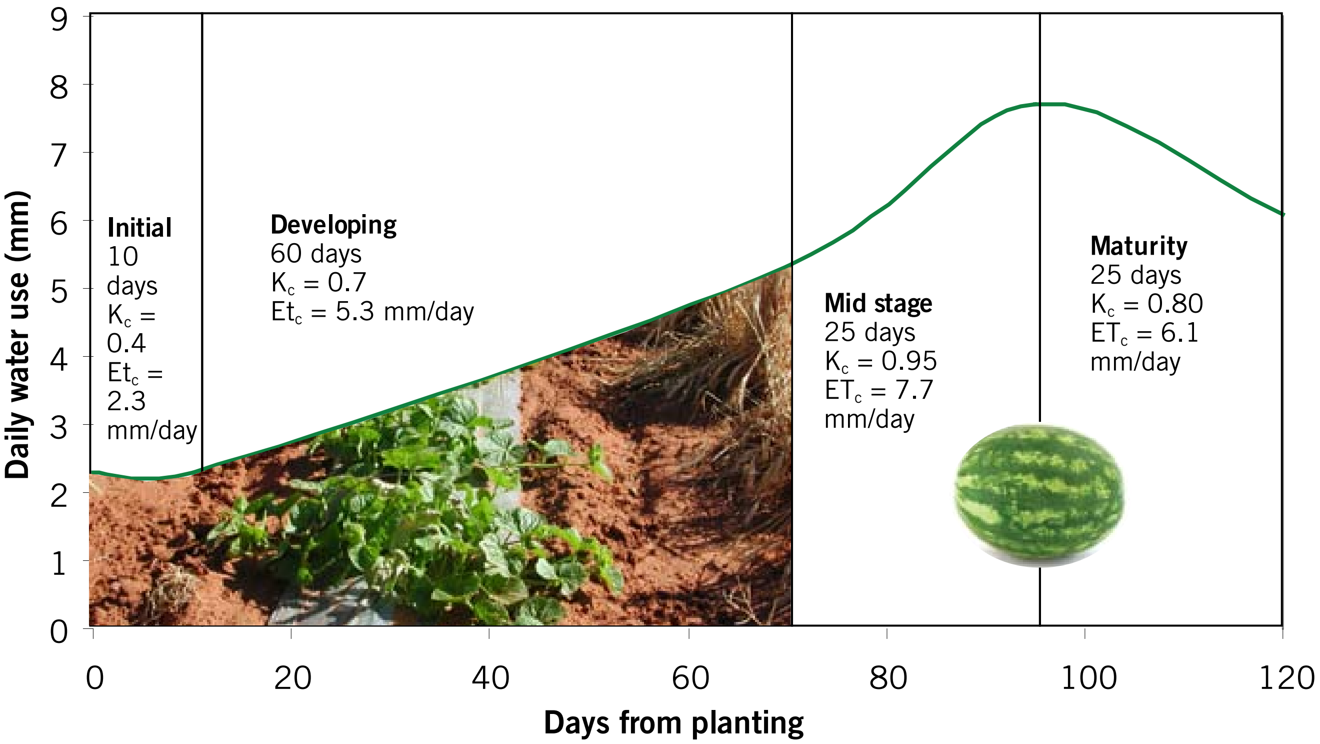
Or

*Crop water use (mm) = **Crop Coefficient (K_c)** x Evapotranspiration (ET_o)*

The crop coefficient relates the crop water use at a particular developmental stage to the evapotranspiration rate of a reference crop.

It is very important to know the difference between a Crop Factor and a Crop Coefficient as they can differ by as much as 30%.

Calculating crop water use ensures that the water needs for a crop are planned ahead, see Figure 4 for an example. Using average evapotranspiration data (ET_o) for a particular district and the Crop Coefficients (K_c) for a crop relative to each growth stage, it is possible to calculate the average water use for a crop.



	Initial Stage	Developing Stage	Mid Stage	Maturity
Crop Coefficient (K_c)	0.4	0.7	0.95	0.8
Evapotranspiration (ET_0)	5.7	7.6	8.1	7.6
Daily crop water use (ET_c)	2.3	5.3	7.7	6.1

Figure 4. *The estimated daily water use of a melon crop at Griffith, NSW.*

Below is an equation that can be used to calculate water use over a season:

Total water required for each growth stage = Length of each stage (days) x Crop Coefficient at each stage (K_c) x average Evapotranspiration during that time (ET_o).

The water used at each stage is then added together to give the total water use budget for the crop. For this example the value is 6.8 ML/ha. This value may seem high, because average data has been used, inflating the total value. A more accurate value can be calculated if actual data relating to specific farming conditions are used.

Problems of water stress

Water stress may arise through an excess of water or a deficiency of water.

Excess water, or flooding, is a problem because it causes stress by limiting the amount of oxygen available to the roots of the plant. This in turn limits respiration in the roots, nutrient uptake and critical root function, resulting in poor plant growth, yield and quality. It also makes the plant more prone to disease.

Stress due to insufficient water is more common and has a number of negative affects on plant growth. A key effect is that photosynthesis is reduced as the stomates close in response to water stress, thus restricting the availability of CO_2. Water flow through the plant is also stopped when the stomata close, reducing the rate of photosynthesis. The result is a loss of yield and quality. Table 2 shows that the relative impact of stress on yield and quality depend on the growth stage of the crop.

Table 2. *Different growth stages are more sensitive to water stress. (Source: Qassim et al., 2002)*

Growth Stages	Sensitivity to water stress
Initial (establishment): from sowing to 10% ground cover	Medium
Crop development: from 10 to 70% ground cover	Medium
Mid-season: (fruit formation) including flowering and fruit setting or yield formation	High
Late-season: including ripening and harvest	Low

Improving the efficiency and effectiveness of water use is the result of managing a number of factors, including water availability, fertility, pests and diseases, crop variety, planting date, soil water conditions at planting, plant density and row spacing. This means that improving water use efficiency requires an understanding of the whole system and should not focus solely on the application of water.

4.Water and Soil

Water and Soil

Key Messages

- Soil properties such as texture and structure strongly influence water storage and availability.
- Readily available water (RAW) is water that plants can easily remove from the soil.
- Irrigation design should be matched to soil type.

Soil properties influencing the movement and storage of water

Soil properties, in particular texture and structure, strongly influence the way water behaves in a soil. These properties affect the movement of water into the soil, drainage and water storage in the soil profile (Figure 1). Of particular importance is the amount of stored water that is readily available for uptake by plant roots.

Figure 1. *Soil profile.*

Before designing an irrigation system, and to optimise water use by plants, it is important to understand how soil properties affect water storage. It is important to have these properties assessed on-farm and the rooting depth of crops also needs to be known.

The reason that texture and structure have such a strong influence on water storage and availability is the size of soil particles and pores, and their arrangement. Soil with large particles and large pore spaces (sand) hold the least amount of water. Clay-rich soil on the other hand has small particles and can store a large amount of water. However, not all of it is available to plants as small pores hold onto water very tightly. Compacted soil has small, disconnected pore space which reduces the amount of water that is available to plants.

Readily available water (RAW) is water that plants can easily remove from the soil. Plants create a suction to do this. A smaller amount of suction is required to remove water from large pores than small pores.

Soil texture

Soil texture is the amount of sand, silt and clay in a soil. It has a strong influence on water storage and availability because of variation in particle size distribution and surface area. Clay particles are small (diameter < 0.002 mm) compared to larger sand particles (diameter 0.02 – 2 mm).

Smaller particles fit together more tightly than larger particles and therefore the pores for air and water are also smaller. Small pores retain water against gravitational forces, drainage and also against plant use, while the larger pores found in sand allow water to drain more freely.

Ideally, a soil will contain a range of pore sizes, larger pores which drain readily so as to prevent waterlogging following soil saturation and smaller pores which store water for plant use. Water held in very small pores is not available to plants because they retain it so strongly. Of most importance for plant growth is the amount of water stored in the soil that is readily available for uptake by plants rather than the total amount of water stored in the soil profile.

The amount of water that can be absorbed by the soil increases as the surface area of the particles in the soil increases. Fine clay has about 10,000 times as much surface area as the same weight of medium-sized sand.

Soil with high organic matter can also retain water very well.

Determining soil texture

It is important that soil texture is determined for the various layers (horizons) of soil within the root zone as it is needed to estimate water available for plant growth.

Soil texture can be determined in the field by the way the soil behaves when a small handful of soil is moistened and kneaded into a ball a bit larger than a golf ball (often referred to as a bolus), and then pressed out between the thumb and forefinger to form a ribbon (Figure 2). Table 1 gives broad field texture classes and is to be used when determining the texture of a soil.

Figure 2. *Formation of a ball and ribbon to determine soil texture. (Source: Anderson et al., 2007)*

Soil structure

Soil structural form is the arrangement of the solid components of soil and the spaces in between.

Ideally, soil should have pores for the flow of water and gases, and pores that contain water and dissolved nutrients for plant growth.

In badly compacted soil the pore space is reduced so water transmission through the soil is slowed and water storage and aeration is reduced. A surface crust increases runoff, which reduces the efficiency of rainfall and irrigations. A compacted soil will have reduced readily available water (RAW), compared to a soil with the same texture but with better structural form. In a compacted soil plants may experience moisture stress, even if there is sufficient rainfall and irrigation, because of a reduction in RAW.

Root growth is also impeded in a compacted soil. In addition to a reduction in RAW in a compacted soil, the roots are not able to harvest water from as large an area as would be possible if their growth was not restricted. This can mean the difference between crop success and failure in times of water shortage.

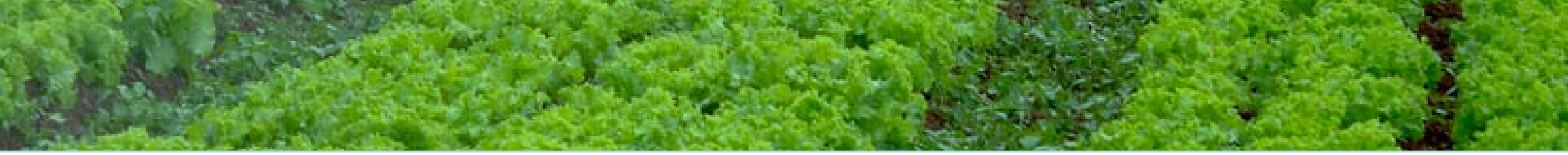
It is important to maintain good structural form. Methods include improving organic matter content, encouraging soil fauna such as earthworms, avoiding cultivation when it is too dry or too wet and implementing controlled traffic farming. If a soil is badly compacted structural form needs to be firstly regenerated using biological solutions (e.g. rotation crops) and appropriate tillage strategies.

Water storage for plant growth

After prolonged heavy rainfall, when the soil profile is full of water, including all of the air spaces, the soil is said to be 'saturated'. After the surplus water drains and there is no more free drainage the soil is said to be at its maximum water storage capacity or full point, often referred to as 'field capacity' (FC). Field capacity is at a tension of approximately -8 kPa.

Table 1. *Broad field texture classes. (Based on: McDonald et al., 1990)*

Field texture group	Description	Approximate clay content
Sand	Nil to slight coherence. Ribbon of 0–15 mm.	Less than 10%
Sandy loam	Coherent but very sandy to touch. Ribbon of 15–25 mm.	10–20%
Loam	Coherent, spongy and greasy feel with no obvious sandiness or silkiness. Ribbon of about 25 mm.	About 25%
Silt loam	Coherent, very smooth to often silky when manipulated. Ribbon of about 25 mm.	About 25% and with silt 25% or more
Sandy clay loam	Strongly coherent, sandy to touch with medium size sand grains visible in finer matrix. Ribbon of 25–40 mm.	20–30 %
Clay loam	Coherent plastic bolus. Smooth to touch with no obvious sand grains. Ribbon of 40–50 mm.	30–35%
Light clay	Plastic bolus. Smooth to touch with slight resistance to shear. Ribbon of 50–75 mm.	35–40%
Medium to heavy clay	Plastic bolus. Smooth to touch. Feels like normal to stiff plasticine. Moderate to firm resistance to shear. Ribbon of 75 mm or more.	40% or more



As water is removed by plants and by evaporation from the soil surface it becomes more and more difficult for plants to extract water as it clings more tightly to soil particles and in small pore spaces. When water extraction becomes difficult for plants and more water is required to maintain growth rates, the soil is said to be at the 'refill point'. Refill point for horticultural crops lies between a tension of -20 and -60 kPa.

Eventually, if the soil continues to dry, it will hold some water which cannot be extracted by plant roots and plants wilt and cannot recover. This is called the 'permanent wilting point' (PWP). It is important to note that plant production will slow/stop before PWP is reached (a tension of -1500 kPa).

Soil within the root zone needs to be able to store as much water as possible in the plant available range but also drain well enough so that aeration is quickly re-established after irrigation or rainfall. Plants grow best when they have a suitable balance of water and air in their root zones (Figure 3).

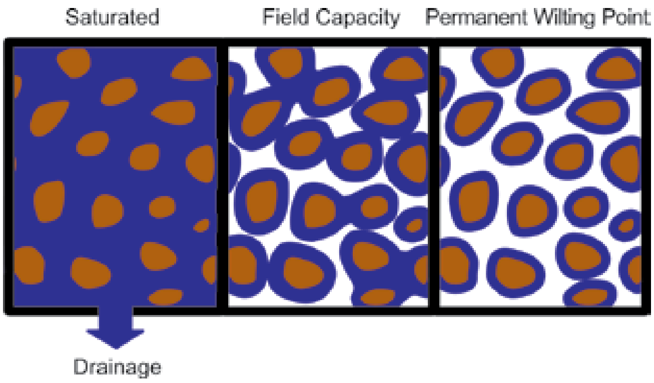


Figure 3. *The balance of water and air in the soil: Left, saturated soil (soil contains no air); Centre, soil at field capacity (good balance of air and water); Right, soil at wilting point (no water available to plants). (Source: Anderson et al., 2007)*

There are three types of stored soil water:

- Readily available water (RAW) – water held between field capacity and refill point.
- Plant available water (AW) – water held between field capacity and permanent wilting point.
- Unavailable water – water stored in very small pores or held so tightly around soil particles that it cannot be extracted by plant roots.

Estimating soil water holding capacity

Soil texture and structure information can be used to roughly estimate soil water holding capacity, which is important in planning irrigation design and operation. Ideally, soil condition should be assessed before a new field is developed for vegetable production so that the irrigation design can be matched to the soil types found. If this is not done then some areas will be over-watered, while others will be under-watered. The amount of water to be applied per irrigation event, and the time between irrigation events will vary between soil types.

The pore size distribution varies between sands, loams and clays. Sands have lots of large pores while clays have lots of small pores. Water drains readily from sand as it has large pores making water unavailable to plants. Water is held very tightly in clay due to its small pores and this water is also unavailable to plants. The soil moisture characteristics of a sandy soil and a clay-rich soil are summarised in Figure 4. The variability in plant available water across textures types and structural form is shown in Figure 5.

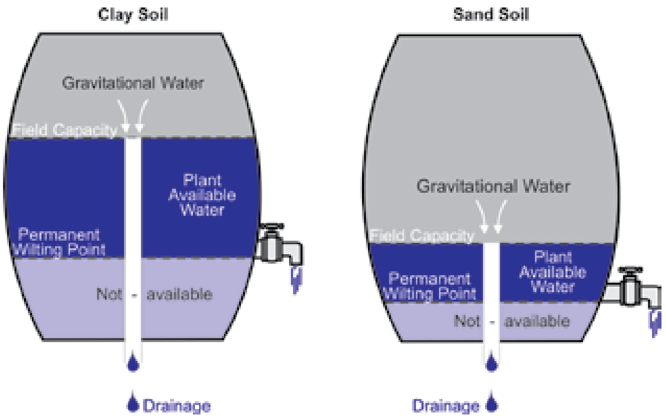


Figure 4. *The soil moisture characteristics of a clay and a sand soil. (Source: Anderson et al., 2007)*

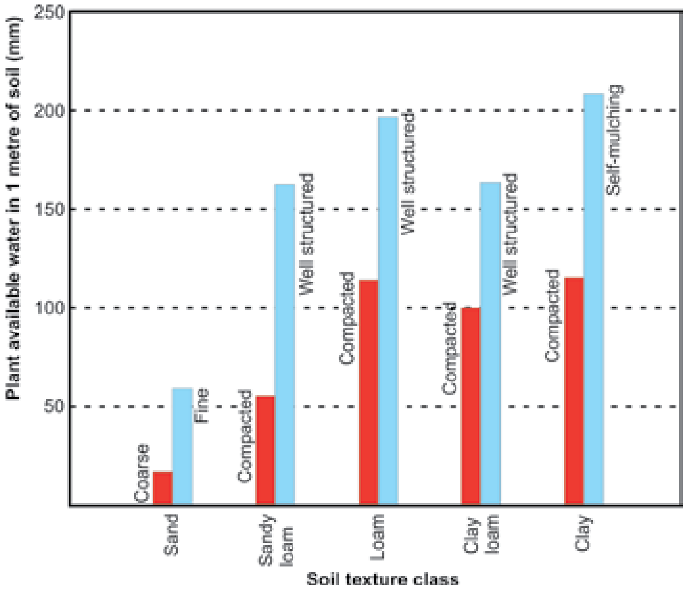


Figure 5. *The amount of water that can be held in the soil varies with soil texture and structural form. (Source: Anderson et al., 2007)*

Calculating readily available water

To calculate RAW:

1. Estimate effective root depth (this can be done by examining roots of past crops in a soil pit or using published estimates of effective root depths of the crop to be grown, Table 2)
2. Measure the depth (in metres) of each soil layer in the root zone
3. Determine soil texture for each layer
4. Identify the RAW (in mm/m) for each texture type identified in the root zone (Table 3)
5. Multiply the thickness of each soil layer by its RAW value to determine the RAW for each soil layer
6. Add the RAW values for each soil layer together to the depth of the root zone to obtain the total RAW for the root zone or add the RAW values for each soil layer to obtain the total RAW for the soil profile (to a depth of 1.5 m for example)

Ideally rooting depths will be observed on-farm. Rooting depths will vary with published data as a response to local soil conditions. As well as physical properties such as compaction influencing root growth, chemical properties such as salinity, sodicity and nutrient toxicities act as barriers to root growth.

Note that on-farm soil sampling and soil moisture monitoring can be used to refine published RAW values for a particular site over time. RAW values will be reduced if a layer contains significant amounts of coarse fragments such as gravel.

Table 2. *Typical rooting depths for a range of vegetable crops. (Source: Qassim et al., 2002)*

Crop	Rooting depth (m)
Tomato	0.5 – 1.5
Onion (green or dry)	0.3 – 0.6
Watermelon	0.8 – 1.5
Carrot	0.5 – 1.0
Lettuce	0.3 – 0.5
Broccoli	0.4 – 0.6
Cabbage	0.5 – 0.8

Table 3. *Readily available water for a range of water tension levels for different soil textures. (Source: NSW Agriculture, 2001 and Quassim et al., 2002)*

Soil Texture	RAW (mm/m)				AW (mm/m)
	A[1] −8 to −20 kPa	B[2] −8 to −40 kPa	C[3] −8 to −60 kPa	D[4] −8 to −100 kPa	E −8 to −1500 kPa
Sand	35	35	35	40	60
Sandy loam	45	60	65	70	115
Loam	50	70	85	90	150
Sandy clay loam	40	62	71	101	143
Clay loam	30	55	65	80	150
Light clay	25	45	55	70	150
Medium – heavy clay	25	45	55	65	140

[1] Column A for water-sensitive crops such as vegetables and some tropical fruits

[2] Column B for most fruit crops and table grapes (most tropical fruits are irrigated between -25 and -40 kPa)

[3] Column C for wine grapes (except during partial root zone drying), most pastures and field crops such as maize and soybeans

[4] Column D for lucerne, annual pastures and hardy crops such as cotton, sorghum and winter cereals

Example: A cabbage crop has an effective root zone of 70 cm. The soil in the paddock has 3 soil layers: a sandy clay loam (0 – 20 cm), a clay loam (20 – 50 cm) and a light clay (50 – 100 cm). The refill point is -20 kPa.

Calculations for root zone RAW:

1. *The effective root depth is 0.7 m*
2. *For layer 1 the depth is 0.2 m, for layer 2 the depth is 0.3 m (0.5 m – 0.2 m) and for layer 3 (remembering that the effective root zone is 0.7 m) the depth is 0.2 m (0.7 m – 0.5 m)*
3. *Layer 1 texture class is sandy clay loam, layer 2 texture is clay loam and layer 3 is light clay*
4. *RAW for the texture class of layer 1 is 40 mm/m, for layer 2 is 30 mm/m, and for layer 3 is 25 mm/m*
5. *Layer 1 RAW = 0.2 m X 40 mm/m*
   = 8 mm

   Layer 2 RAW = 0.3 m X 30 mm/m
   = 9 mm

   Layer 3 RAW = 0.2 m X 25 mm/m
   = 5 mm
6. *Root zone RAW = Layer 1 RAW + Layer 2 RAW + Layer 3 RAW*
   = 8 mm + 9 mm + 5 mm
   = 22 mm

Therefore for this example, when the soil dries to refill point, 22 mm of water would need to be applied to bring the soil to field capacity.

Determining the timing and amount of irrigation

5. Determining the Timing and Amount of Irrigation

Key Messages

- Determining an irrigation schedule that closely matches the water needs of a crop can be based on one or more of the following methods:
  - Visual observation (personal experience, plant and soil condition).
  - Soil moisture monitoring.
  - Calculating evapotranspiration losses.
- Growers need to choose the method that best suits their operation.

Personal experience and visual observation of the plant and soil

One of the most common methods used by vegetable growers to schedule irrigations is by observing the crop and assessing the feel and appearance of the soil. Visual observation is a quick and easy method and is popular because it does not need investment in equipment or technical support.

Table 1 can be used to assist in estimating the available water in a soil.

The downside to using visual observation as a method to schedule irrigations is that it may not always be accurate and extensive experience is required to use it effectively. It is recommended that visual observation be used to gain preliminary information to be used in combination with other methods such as using tensiometers or evapotranspiration data to schedule irrigations.

With experience growers can learn to use visual observations successfully, especially when decisions are supported by other methods.

Using visual observations alone makes it difficult to assess subsoil moisture conditions. To determine how deep irrigation water or rainfall has penetrated, the soil needs to be examined using a spade or auger. Over or under irrigating is easy to do when not monitoring soil moisture in the subsoil with technical equipment. This can result in decreases to crop yield and quality.

Table 1. *The appearance of soil at different moisture contents. (Source: Cornish et al., 1987)*

Available water	Sands and sandy loams	Loams, clay loams and clays	General comment
Above field capacity	Free water can be squeezed out of the ball of soil.	Soil is very sticky and sloppy and when squeezed oozes water.	Soil waterlogged. No air can get to the roots.
100% (field capacity)	Upon squeezing no free water appears on the soil, but wet outline of ball is left on hand.	Soil sticky. No free water appears on the soil when ball is squeezed, but wet outline of ball is left on hand. Possible to roll long thin rods between fingers.	Plenty of water available to the plant, and enough air.
75%	Slightly coherent. Forms a weak ball under pressure but breaks easily.	Soil coherent. Soil has a slick feeling and ribbons easily. Will not roll into long thin rods.	Adequate water and air and plant grows well.
50%	Appears dry. Tends to ball under pressure but seldom holds together.	Soil coherent. Forms ball under pressure. Will just ribbon when pressed between finger and thumb.	Just enough water available to the plant.
25%	Appears dry, will not form a ball under pressure.	Somewhat crumbly but will form a ball under pressure. Will not ribbon between finger and thumb.	Past refill point; plant growth has ceased.
0 – 25 % (wilting point)	Dry, loose, flows through fingers.	Crumbly, powdery. Small lumps break into powder. Will not ball under pressure.	Desperately needing water; plants will die soon.

Soil moisture monitoring

Another method of determining irrigation scheduling is to use soil moisture monitoring equipment. Using soil moisture monitoring equipment is particularly important for gaining information about subsoil moisture. This equipment helps to determine to what depth roots are extracting water from, what depth an irrigation or rainfall has penetrated, and when to stop irrigating.

Soil moisture monitoring is discussed in more detail in Chapter 6.

Calculating evapotranspiration losses

Historical evapotranspiration data is used to calculate a general water budget for a crop. A more accurate estimate of plant water use is based on local daily evapotranspiration data which can be obtained from Departments of Primary Industries or the Bureau of Meteorology. This data is used to schedule irrigation events by replacing the water lost from the plant:soil system by a process of soil moisture accounting.

Irrigation events are scheduled when the soil moisture falls below the RAW (Readily Available Water) calculated for the soil.

Soil moisture accounting tracks, on a daily basis, the amount of water going into the system (rainfall or irrigation) and the amount of water going out (rate of crop water use) as shown in Table 2. When the soil moisture deficit falls below the RAW then an irrigation event must occur to replenish the soil moisture.

Steps for calculating the daily soil moisture balance using evapotranspiration data

Daily crop water use (ET_c) (mm/day) = ET_o X Crop Coefficent (K_c)

1. Calculate the readily available water for the soil (RAW) as shown in Chapter 4.
2. Record daily evaporation figures ET_o from weather station, local DPI or Bureau of Meteorology web site http://www.bom.gov.au
3. Multiply Evapotranspiration value (column A) by the appropriate crop coefficient (K_c) value (Column B) to obtain the daily crop water use (Column C).
4. Determine how much water is needed to be applied based on the efficiency of your irrigation system by dividing Column C by the efficiency of the irrigation system**. In this example the system is operating at 0.8 efficiency.
5. Record daily rainfall and calculate effective rainfall or irrigation (Column E).
6. Calculate the change in daily water balance (Column E – Column D).
7. Calculate the remaining available water (Column G from previous day + Column F for current day).
8. When Column G falls below the RAW for that soil an irrigation event is required to bring the soil profile back to field capacity.

The day after an irrigation event the soil is saturated and crop water use is assumed to be zero.

Table 2. *Calculating the daily soil moisture balance using evapotranspiration data - RAW = 16 mm in this example. (Adapted from: NSW Agriculture, 2001)*

	A	B	C	D	E	F	G
Date	ET_o Evapo-transpiration	K_c Crop Coefficient	ET_c (A x B) Daily crop water use	ET_c/ Efficiency Example = 0.8	Effective rain* or irrigation (mm)	Daily change in water balance (E – D)	Remaining available water (G + F)
8th Jan	8.0	0.95	7.6	9.5	0	−9.50	−9.50
9th Jan	8.2	0.95	7.8	9.8	10 rain	+0.2	−9.30
10th Jan	8.1	0.95	7.7	9.6	0	−9.6	−18.9
11th Jan	8.2	0.95	7.8	9.8	30 irrigation	20.2	+ 1.3 drainage means 0.0

* Effective rainfall = during spring, summer and autumn periods, subtract 5 mm from the total daily rainfall. In winter, all the rainfall is assumed to be effective.

** Application efficiency = the ratio of the average depth of irrigation water stored in the root zone for crop consumptive use to the average depth applied, expressed as a percentage.

6. Measuring & Interpretation of Soil Moisture

Key Messages

- What to measure: plant or soil water status?
- Types of measuring equipment.
- When to water and how much to apply?

Measuring the soil moisture content is a way of monitoring the water available to the plant for growth. When the water at any depth falls below the refill point or where there is no remaining readily available water (RAW) then an irrigation event must be scheduled.

Types of measuring equipment

There is a wide range of technical soil moisture monitoring equipment currently available for growers to use to help manage and monitor water use in the field.

The types of soil moisture monitoring equipment available can be divided into two categories.

Soil Suction Measurement Systems

- Tensiometers
- Resistance/Gypsum Blocks
- Wetting Front Detectors

Soil Moisture Content Measurement Systems

- Capacitance - Frequency Domain Reflectometry devices (FDR)
- Time Domain Reflectometry devices (TDR)
- Neutron Probe

Soil suction measurement systems

Soil suction devices measure the (negative) pressure required by the plant to be able to extract water from the soil. This effort or force from the plant on the soil to draw the amount of water it needs to grow can be measured as tension. The drier the soil, the more tightly the water is held, and the more energy the plant has to use to extract the water from the soil. Therefore devices that measure soil water potential are very good indicators of the stress plants are under.

These devices enable growers to keep crop stress to a minimum by managing irrigation to ensure the correct soil water potential is maintained. For water-sensitive crops, such as vegetables, a tension of –20 kPa is considered the refill point. The RAW is the amount of water that is held between field capacity –8 kPa and –20 kPa.

However, the devices do not inform the grower as to the volume of water that is required to be applied. Grower experience and knowledge and adjustment of duration and intervals of irrigation are required to determine the volume of water that needs to be applied.

Figure 1. *A tensiometer.*

Tensiometers

A tensiometer (Figure 1) is essentially a tube filled with water that has a porous ceramic tip which is buried in the soil at the depth/s which soil moisture is to be measured. Tensiometers can be buried at 2 to 3 different depths in the root zone in order to obtain a soil moisture profile. The porous ceramic tip allows water to move freely from the tensiometer to the soil surrounding the tensiometer. Water will move out to the drier soil until the potential within the tensiometer is the same as that of the soil water. A vacuum gauge records the level of suction required by the plant to draw water from the soil. The vacuum gauge can be read manually by the operator, but can also be measured electronically and logged.

Figure 2. *Growers being shown how to use a wetting front detector.*

Resistance blocks

Resistance blocks such as gypsum blocks are made from a porous material with two electrodes embedded in the material. They are buried in the soil and they take on the soil water characteristics of the surrounding soil, creating equilibrium. The electrical resistance within the blocks is measured. The electrical resistance of a block is directly proportional to its water content, which is related to the soil water potential of the soil surrounding the block.

Wetting front detectors

Wetting front detectors (Figure 2) are simple devices that are buried at points of interest and provide information to growers as to when water has reached that point in the soil profile. When soil moisture increases above a set point the detector switches on, or is activated, indicating that water has reached a given depth. When the soil moisture dries to below a set point the detector switches off. Wetting front detectors are often placed near the bottom of the root zone so that they can be used to warn against over-irrigation.

Soil moisture content measurement systems

Instruments that indirectly measure soil moisture content use sensors that are placed in the soil at various depths in the root zone. The sensors measure properties that are closely related to soil water content. Calibration equations can be used to convert the property being measured by the sensor to soil water content.

Capacitance devices

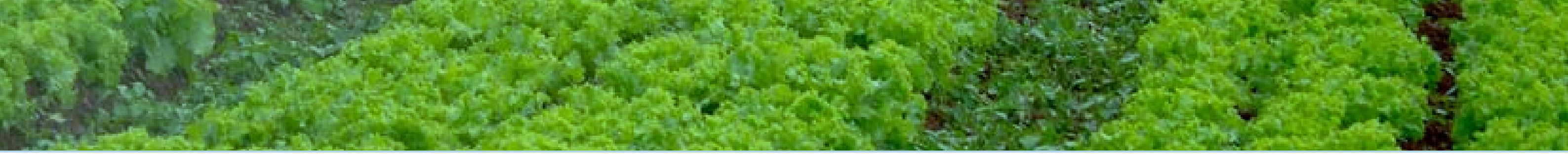
Frequency domain reflectometry (capacitance) devices (Figure 3) utilise the dielectric constant of the soil water media to calculate soil water content. These types of instruments work on the basis that the dielectric of dry soil is much lower than that of water and hence is also lower than that of wet soil.

Soil is placed between two electrical plates to form a capacitor. The soil dielectric is calculated by applying a voltage to the plates and measuring the frequency.

Figure 3. *The photograph on the left shows a C-Probe ® soil moisture system installed in the field and the photograph on the right, shows two EnviroScan ® soil sensors which are used to detect soil moisture. The sensors are enclosed in a PVC tube to protect the electronics from soil and water.*

Time Domain Reflectometry (TDR) devices

TDR devices operate similarly to capacitance devices in that they utilise the dielectric constant of the soil water media to calculate soil water content. An electromagnetic signal is sent down a steel probe which is buried in the soil at the desired depth. The signal reaches the



end of the probe and is reflected back to the control unit. The return time of the signal varies with the soil dielectric constant and therefore relates to the water content of the soil surrounding the probe.

Neutron probes

Neutron probes emit fast moving neutrons. When they collide with hydrogen in the soil they are slowed and deflected. A detector on the probe counts returning slow neutrons. The number of slow neutrons detected can be used to calculate soil water content because changes in the amount of hydrogen in the soil between readings will only come about from changes in water content. A wet soil will contain more hydrogen than a dry soil and therefore more slow neutrons will be detected.

Choosing the right device

With a range of methods and instruments available to monitor soil water content, what factors should a grower consider when deciding which is best suited to their needs?

Devices vary in their simplicity, cost, accuracy and labour requirement for installation, monitoring and servicing. Individual requirements should be indentified before purchasing a soil moisture monitoring device. As a minimum, a soil moisture monitoring instrument needs to provide water content readings for the plant root zone before and after irrigation and rainfall.

Questions to consider before purchasing a soil moisture monitoring device or system include:

- What information does this soil water monitoring device provide?
- What format will the data be in and how useable will it be?
- How labour-intensive is it?
- Does the device suit specific soil type/s and crop/s?
- Capital cost
- Do measurements need to be taken manually or can they be transmitted back to an office?
- Accuracy and repeatability of measurements?
- Will the data be able to be interpreted into meaningful information?
- What expertise is available to help interpret soil water measurements?
- How durable is it and how much maintenance will it need?
- How does water quality and salinity affect the device?

In order to adequately answer the list of questions before purchasing a soil moisture monitoring device more detailed resources are available for growers. Some of the resources available can be found at www.ahr.com.au. Local consultants are also a valuable source of information and knowledge to assist in making the decision.

Interpreting soil moisture data

Interpretation of soil moisture data is critical to making the correct decision of when to irrigate and how much water to apply.

The two main types of soil moisture measuring equipment in is use in Australian vegetable production are:

1. Tensiometers
2. Soil Capacitance Probes

Interpretation of tensiometer data

The correct interpretation of tensiometer data is straightforward because it measures the relative difficulty plants will be experiencing when their roots extract water from the soil at a particular point in time. Table 1 provides some guidelines for interpreting tensiometer readings. Soil type does not strictly affect interpretation, but remember that loam and clay soil types can hold a lot more available water than sandy soil, so the time between irrigations and the critical reading of approximately 20 kPa indicating it is time to irrigate will be greater in a clay soil than for sandy soils.

Interpretation of capacitance data

Capacitance data is usually logged and then can be viewed using software supplied by the manufacturers. There are two ways in which the data can be viewed:

1. Soil moisture at individual sensors
2. Total soil moisture for the depth being monitored

Soil moisture at individual sensors

The data is collected from each sensor and graphed over time. The soil moisture data can be collected at different depths in the soil profile. This type of data can be useful because it shows where in the soil profile the water is being taken from. If water is being extracted from deeper depths it means that the plant is working harder to get water and it can mean that the plant is under water stress.

Total soil moisture for the depth being monitored

The moisture readings from each of the sensors can be added together to give the total soil moisture for the depth of soil monitored. There are three key things to note from Figure 4, which is an example of a total soil profile graph.

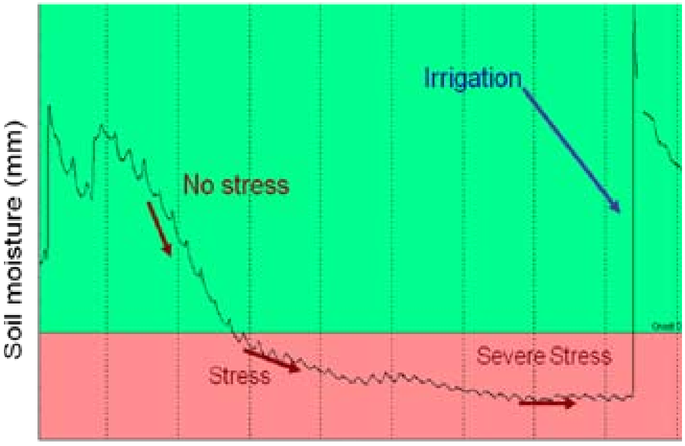
First, notice the irrigations: they are near vertical lines where water is added to the soil by irrigation, or possibly a rainfall event. Second, notice the sawtooth pattern as the soil moisture is used by the plant.

Table 1. *Critical soil tensiometer levels for vegetable crops.(Source: Texas A&M University, 2001)*

Soil moisture status	Tensiometer reading (kPa)	Interpretation
Nearly saturated	0	Nearly saturated soil often occurs for a day or two following irrigation. Danger of water-logged soils, a high water table, poor soil aeration, or the tensiometer may have broken tension if readings persist.
Field capacity	-10	Field capacity. Irrigations discontinued at field capacity to prevent waste by deep percolation and leaching of nutrients below the root zone.
Irrigation range	-20	Usual range for starting irrigations. Most of the available soil moisture is used up in sandy loam soils. For clay loams, only one or two days of soil moisture remain.
Dry	-30	This is the stress range for most vegetable crops.
Extremely dry	-80	Top range of accuracy of tensiometer. Readings above this are possible but many tensiometers will break tension between 80 to 85 kPa.

This pattern is caused by the plant water use during the day and the recharge of moisture from outer lying soil overnight. Thirdly, and most importantly, notice the change in slope of the line as the plants go into water stress. The line flattens out because as the RAW in the soil profile decreases the plant's ability to uptake water slows.

Figure 4. *Severe moisture stress showing the key points in interpretation of soil moisture data.*



When to water and how much to apply using soil moisture monitoring equipment

Using soil moisture monitoring equipment the suggested strategy is:

1. Install soil moisture monitoring equipment.
2. Irrigate the soil fully – aim to fully wet the soil profile across the bed and from the surface to at least 50 cm. A very good way to check this is to install two probes, one in the centre of the bed, and another near the edge of the bed. They can be used to track the movement of water across the bed and down the soil profile.
3. Use the individual sensor data to observe the extent of soil wetting and where the roots are taking up water.
4. Observe the single graph for the whole soil profile, watch for the rate of water uptake to decline (slope of line flattens out). Set this as the ***onset of stress*** point.
5. Fully irrigate the crop to fill the profile. Set this as the ***full point*** using the single line graph.
6. After a few iterations of this, and adjusting irrigation duration and interval, an idea is gathered of how long is needed to irrigate to take the whole profile from a point which is just about at the onset of stress back up to full point. The single line graph can be used to anticipate when the next irrigation is required.
7. Repeat this process for each different soil type, crop and irrigation method.

7. Irrigation Case Studies

Key Messages

- Water stress caused by too much, not enough or irregular irrigation reduces crop yield.
- Irrigation management affects crop quality.
- Objectively measuring soil moisture ensures optimum water management.

Water stress affects crop yield

Plants use energy to extract water from the soil and take it up into the roots, then via the vascular system to the rest of the plant including leaves, flowers and developing fruits. This process uses energy the plant has produced from photosynthesis and the drier the soil the more energy the plant has to allocate to taking up water. The result in dry soil is less energy goes into producing leaves and fruit and in turn commercial yields are reduced.

This means that forcing plants to work hard to take up water will be at the expense of growth and yield.

When watermelon plants were supplied with their full water requirement of about 7 ML per hectare, in a sandy soil and hot climate, fruit yields of around 85 tonne per hectare were achieved (Figure 1). When the crop was supplied with less water, down to about 4 ML per hectare, yields dropped by 40% to about 50 tonnes per hectare.

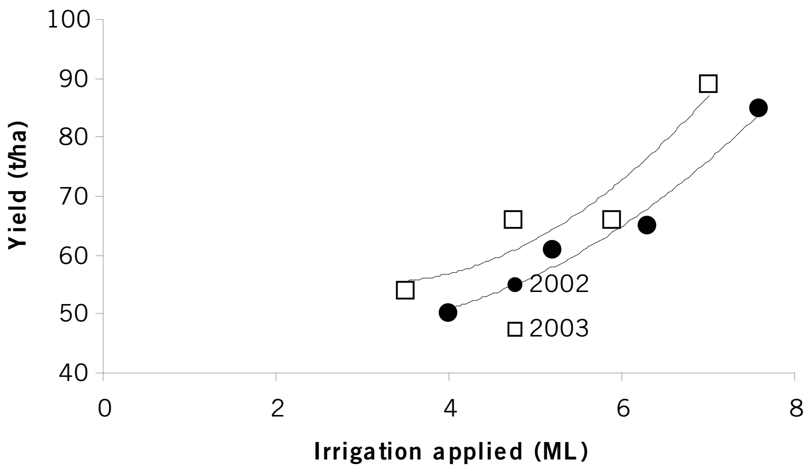


Figure 1. *The effect of irrigation water applied on the yield of watermelons. (Source: Simsek et al., 2004)*

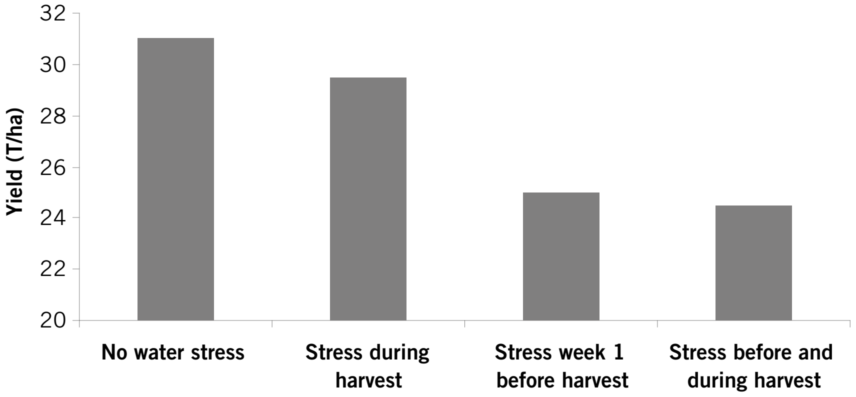


Figure 2. *Yield of rockmelons (var. Dubloon) grown in Bourke, NSW, and affected by imposing a water stress at different stages of late fruit development. (Source: Long et al., 2006)*

The data in Figures 1 and 2 show that supplying plants with insufficient water reduces yield, but what happens when vegetable crops are given too much water? An irrigation trial on seedless watermelons at Condobolin, NSW, where the crop was already being supplied with adequate water, tested the effect on yield when additional water was applied.

Figure 3 shows that when the optimum water requirement for a watermelon crop in this area (about 3.5 – 4.0 ML) was applied, a yield of 60 tonnes per hectare was achieved. When the amount of irrigation water was increased to 4.8 and 5.7 ML per hectare, the yield dropped to 50 and then to 40 tonnes per hectare respectively.

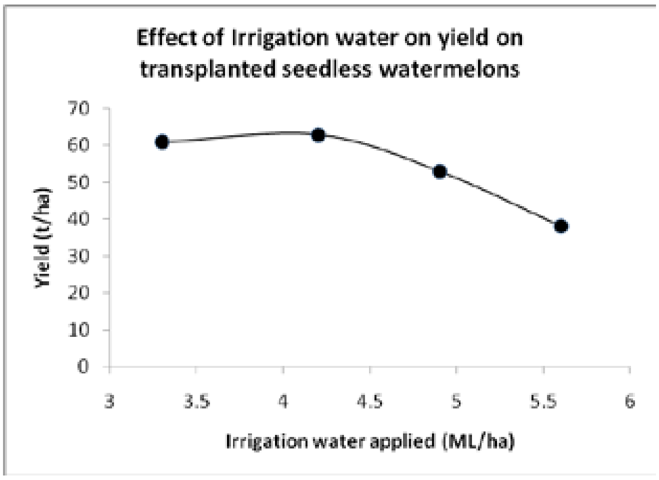


Figure 3. *The yield of seedless watermelon in response to increasing irrigation water supply above optimum. (Source: Rogers, 2007)*

Water stress affects quality

Supplying crops with the right quantity of water is not only important for maximising yield. The impact of water quantity on quality follows a similar trend to that of yield. When crops such as lettuce, rockmelons and watermelons are given insufficient or irregularly applied water, their quality declines.

Irregular irrigation means that plants are likely to be under water stress for some of the time, and overwatered at other times. The example shown in Figure 4 shows personal watermelons grown using well-managed irrigation compared to a more erratic water management plan. It can be seen that the well managed irrigation resulted in more even fruit development compared to the wide range in fruit maturity which resulted from irregular watering.

This change in irrigation practice had a major impact on the harvestable yield and profitability of this crop as seen in the photos below.

Erratically watered crop

Well watered crop

Figure 4. *On the left is an example of an erratically watered crop and on the right is an example of a well watered crop.*

Measuring soil moisture can keep plants growing in the zone of readily available water

The importance of supplying water to plants in the right quantity and at the right time is clearly shown in the previous photos, and this is very difficult to achieve without some objective information about the water status of the soil.

Figure 5 shows the corresponding soil moisture data for the seedless watermelon crops pictured in Figure 4. It shows the effect on soil moisture of using objective soil moisture data to manage irrigations versus a “gut feeling” approach.

Before the red line, irrigations were managed by the feel of the soil, and the appearance of the crop. To the right of the red line, soil moisture data together with irrigation records (duration and frequency of previous irrigations) were used to plan the irrigations for the remainder of the crop. The change in uniformity of soil moisture is dramatic. Once objective measurements were used, soil moisture rarely dropped into the pink water stress zone compared to earlier when the crop experienced water stress on several occasions. Unnecessary irrigations, which would have been overwatering the crop, were also avoided.

The result of this improved water management was the uniform, high quality fruit shown in the photos (right panel) compared to the irregular fruit shown in the photos (left panel).

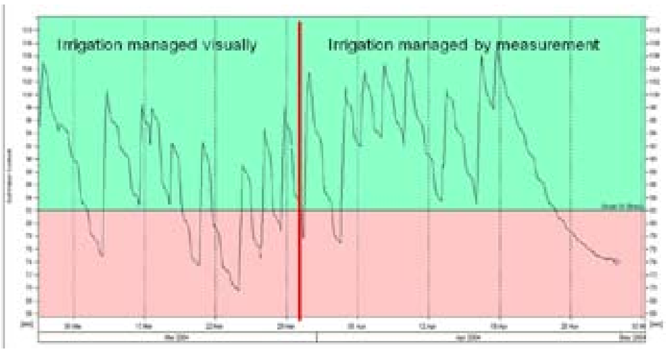


Figure 5. *Total available soil moisture in the top 50 cm of soil in a personal watermelon crop.*

8. Further information & References

WEBSITES

NSW DPI website: Water and Irrigation
http://www.dpi.nsw.gov.au/agriculture/natural-resources-and-climate/water

Information on: types of irrigation systems; soil moisture monitoring; irrigation scheduling; irrigation management for vegetable crops; water use efficiency; and information about irrigation in NSW by region and training courses offered by PROfarm, such as Waterwise on the Farm.

NSW DPI website: Vegetables
http://www.dpi.nsw.gov.au/agriculture/horticulture/vegetables

Information on: best practice guidelines for growing vegetables; best practice irrigation guidelines for vegetables; and soil management information.

Victorian DPI Website: Information Notes - Vegetables
http://www.dpi.vic.gov.au/dpi/nreninf.nsf/LinkView/F35B1CAC4054922BCA256BC8000291D4

Information on: irrigation including estimating vegetable crop water use with moisture-accounting method; how to use tensiometers; and irrigation scheduling for vegetable crops.

Irrigation Industry Information Network
http://www.irrigate.net.au/management/on_farm/index.shtml

Information on: on-farm irrigation including best management practices; crop management; soils; monitoring systems; and water use efficiency. Includes links to information from Departments of Primary Industries and other relevant organisations.

PIRSA website: Water Management
http://www.pir.sa.gov.au/pirsa/nrm/water_management

Links to information on: irrigation best management practice; irrigation efficiency; and crop coefficients.

Growcom Website: Water for Profit
http://www.growcom.com.au/home/inner.asp?pageID=50&main=26&sub=37

Information on: monitoring systems; irrigation management; scheduling calculation sheets; and irrigation system evaluation.

Queensland Rural Water Use Efficiency Initiative
http://www.nrw.qld.gov.au/rwue/index.html

Links to: irrigation fact sheets, which are arranged by topic; a water use efficiency database which can be searched for abstracts of research on irrigation issues; and case studies which present growers experiences with new irrigation systems and practices.

South Australian Murray-Darling Basin Natural Resources Management Board Website: Irrigation Management
http://www.samdbnrm.sa.gov.au/BoardProjects/IrrigationManagement/OutcomesandFactSheets/tabid/1570/language/en-AU/Default.aspx

Contains irrigation management fact sheets including topics such as how much water to apply, soil moisture monitoring tools and soil water.

Department of Agriculture WA: Irrigation
http://www.agric.wa.gov.au/search/search.cgi?collection=external&form=custom&meta_y_and=0LWE0WATER0IRR0&sort=date

Contains fact sheets including information on soil moisture monitoring tools, irrigation best management practices and irrigation systems.

Department of Primary Industries Queensland: Managing Water Resources
http://www.dpi.qld.gov.au/cps/rde/dpi/hs.xsl/4789_4346_ENA_HTML.htm

Information such as water balance scheduling and use of soil moisture monitoring tools.

Vegetables WA: Efficient Irrigation of vegetables on sands
http://www.vegetableswa.com.au/irrigation.index.asp

Information on: good irrigation management; soil moisture monitoring in sand; and calculating water requirements.

PUBLICATIONS

SOILpak for vegetable growers
Available from NSW DPI bookshop.
http://www.agric.nsw.gov.au/reader/soil-management-guides/soilpak-vegetable-growers
This publication is intended for growers, extension officers and consultants, and is aimed at helping vegetable growers to make the right soil management decisions.

Best Practice Guidelines for Growing Vegetables
Leigh James, Jim Murison, Bill Yiasoumi and Ashley Senn. This publication can be downloaded free of charge from:
http://www.dpi.nsw.gov.au/agriculture/horticulture/vegetables/popular/best-practice

Best Management Guidelines for Irrigation of Melons, Carrots and Onions or Best Management Guidelines for Irrigation of Melons; Carrots and Onions.
Available from NSW DPI bookshop.
http://www.dpi.nsw.gov.au/agriculture/natural-resources-and-climate/water/irrigation/crops

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