2.1 Irrigation scheduling

David Wigginton
DW Consulting Services

Emma Brotherton
formerly Qld Department of Primary Industries and Fisheries

Bec Smith
DAFF Queensland

Guy Roth
formerly Cotton CRC

Dallas Gibb
formerly Cotton CRC, NSW DPI

Stefan Henggeler
Integra Management Systems

Key points

- Irrigation scheduling is the decision of when and how much water to apply to an irrigated crop to maximise crop productivity.
- Evapotranspiration (ET) is the combined loss of water to the atmosphere due to evaporation from soil and plant surfaces, and transpiration through plants.
- Crop evapotranspiration (crop water use) calculation and/or soil moisture monitoring can be used to schedule irrigations.
- Plant response to stress varies with the timing and degree of stress, and crop development stage.
- Soil probes do not need to be calibrated to analyse trends, but should not be used to infer total water use

Irrigation scheduling in Australia is difficult because of the variable and unpredictable climate, frequent summer storms and changes to prevailing air temperatures. Correct irrigation scheduling improves water use efficiency, reduces water-logging, controls crop canopy development, quantifies the effectiveness of rain and allows better management of soil structure issues.

This WATERpak topic provides an understanding of crop evapotranspiration and soil water. It also explains how to schedule irrigations and interpret the data collected from soil moisture measuring devices. Additional information that complements this chapter can be found in:

- *Chapter 2.3* - Tools and information for irrigation decision making
- *Chapter 2.4* - Measuring plant water status
- *Chapters 3.1, 3.2, and Section 4* - Irrigation management for cotton and various grains crops
- Chapters 2.2 and 3.3 - Managing Irrigation with limited water

Evapotranspiration (ET)

Evapotranspiration (ET)is the combined loss of water to the atmosphere due to evaporation from soil and plant surfaces, and transpiration through plants.

Transpiration results from the vapourisation of water within plant tissues and its subsequent loss through the small openings on the plant leaf called **stomata**.

Evaporation is the conversion of water from liquid to vapour.

Reference Evapotranspiration (ET_0) is the loss of water to the atmosphere by evaporation and transpiration from a reference crop resembling well-watered green grass with a uniform height of 120 mm. The concept of reference evapotranspiration is used to represent evaporative demand independent of crop and management characteristics at a particular location. By applying an appropriate coefficient, the reference ET value can be used to estimate crop evapotranspiration (ET_c) and the evaporation losses from storage and reticulation systems.

Crop Evapotranspiration (ET_c) describes the actual ET of a crop given standard conditions of optimum soil water, excellent management conditions, large fields and full production. Understanding and determining crop evapotranspiration is critical for scheduling irrigations to meet the crops water use demands and to optimise crop production.

The ET rate is normally expressed in millimetres (mm) per unit time (often mm/day) – it represents the amount of water evaporated from a cropped surface in units of water depth.

100 mm depth of water is equal to 1 ML of water per Ha

Factors Affecting Evapotranspiration

Weather

Radiation

Air temperature

Humidity

Wind speed

The evaporation power of the atmosphere is expressed by the reference crop evapotranspiration (ET_0), which represents the ET from a standardised vegetated surface (well watered grass). Calculation of ET_O is generally performed by automatic weather stations, software packages or ET data providers (such as SILO). Some further information is included in Chapter 2.8.

The current standard for calculating ET_O is the Penman-Monteith method – also referred to as the FAO 56 method. Calculations based on pan evaporation are no longer used as the standard.

Crop

Crop type

Variety

Crop Development stage

These factors affect the rate of ET_C from crops grown in large, well-managed paddocks. Differences in crop height, reflection, ground cover, resistance to transpiration, etc., will result in different ET_C levels in different crop types under identical environmental conditions.

Environmental and Management Conditions

The actual crop evapotranspiration may be influenced by factors that impact on the ability for the standard conditions mentioned above to be satisfied such as:

- Soil salinity
- Inadequate nutrition
- Soil compaction
- Diseases and pests
- Cultivation and irrigation practices
- Windbreaks which reduce wind velocities across the adjacent field
- Irrigation systems that apply water directly to the root zone of crops (limiting evaporation losses as soil surface is dry)
- Surface mulches which substantially reduce soil evaporation when crops are small.

Where these factors are significant, calculation of ET_C should be modified accordingly.

Determining Crop Evapotranspiration

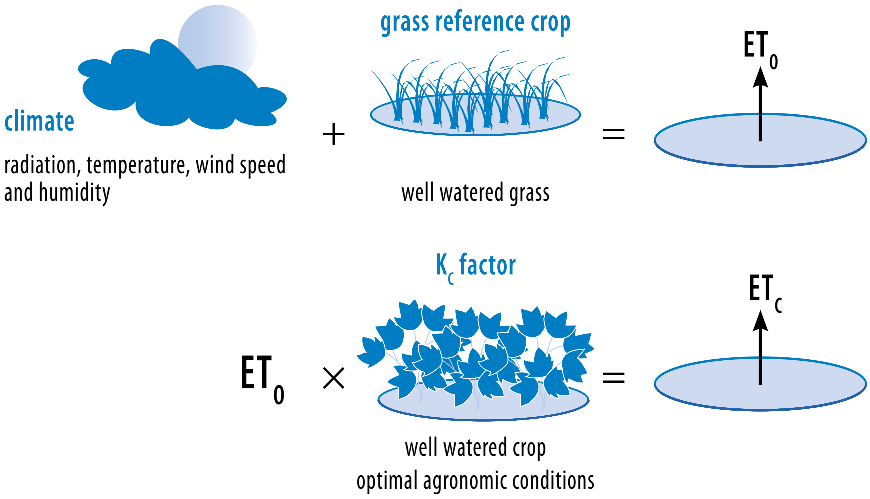
Evapotranspiration is difficult to measure, and is therefore only undertaken in scientific studies using methods such as the Bowen Ratio or Eddy Covariance. For practical purposes, reference evapotranspiration (ET_O) data is available from weather providers (e.g. Bureau of Meteorology or SILO) or from some automatic weather stations (AWS),

A Crop Coefficient (K_C) is used to convert the weather derived Reference Evapotranspiration (ET_O) to an estimate of Crop Evapotranspiration (ET_C) using the following formula:

$$ET_c = K_c \times ET_0$$

The relationship between Reference Evapotranspiration (ET_O) and standard Crop Evapotranspiration (ET_C) through the Crop Coefficient (K_C) is represented in Figure 2.1.1.

Figure 2.1.1. The relationship between Reference Evapotranspiration (ET_0) and standard Crop Evapotranspiration (ET_c)



Source: Allen, R.G. *et al* (1998) Crop evapotranspiration: guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper 56.

The K_c integrates the effect of characteristics that distinguish the crop from the grass reference crop used to calculate ET_0. Different crops have different K_c values due to different crop characteristics. The K_c value also changes over the growing season with changes in crop development and with changes affecting soil evaporation. Estimates of K_c values for the major irrigated crops are presented in Table 2.1.1.

Table 2.1.1: Crop Coefficients (K_c) for major irrigated field crops.

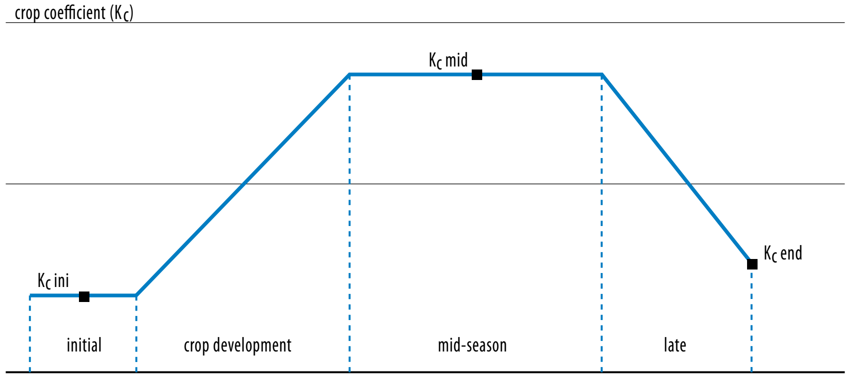
Crop	K_c initial	K_c mid-season	K_c end of season
Barley	0.30	1.15	0.25
Chickpea	0.40	1.00	0.35
Cotton	0.35	1.15 – 1.20	0.70 – 0.50
Maize	0.30	1.20	0.35
Navy bean	0.40	1.15	0.35
Peanut	0.40	1.15	0.60
Sorghum	0.30	1.00 – 1.10	0.55
Soybeans	0.40	1.15	0.50
Sunflower	0.35	1.15	0.35
Wheat	0.30	1.15	0.25

Source: Allen, R.G. *et al* (1998) Crop evapotranspiration: guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper 56.

The crop development stages used to select a K_c value (Figure 2.1.2) are:

1. Initial stage – planting until 10% ground cover.
2. Crop development stage – 10% to effective groundcover (around 70–80%).
3. Mid-season stage – 70–80% groundcover to the start of maturity.
4. Late season stage – the start of maturity until harvest.

Figure 2.1.2. Example Crop Coefficient curve.



Example:

We want to determine the crop water use over a period of a week in mid February for a crop of soybeans. The soybeans are in their mid-season phase, so the crop coefficient (K_c) will be 1.15 (from Table 2.1.1).

Daily crop water use (ET_c) = $ET_0 \times K_c$

The following table contains the ET_0 data obtained from SILO as well as the calculations of daily ET_c:

Date	*ET_0*	*K_c*	*Daily Crop Water use ET_c mm/day*
15 Feb	*4.6*	*1.15*	*5.3*
16 Feb	*3.1*	*1.15*	*3.6*
17 Feb	*4.4*	*1.15*	*5.1*
18 Feb	*4.2*	*1.15*	*4.8*
19 Feb	*5.5*	*1.15*	*6.3*
20 Feb	*4.4*	*1.15*	*5.1*
21 Feb	*5.7*	*1.15*	*6.6*

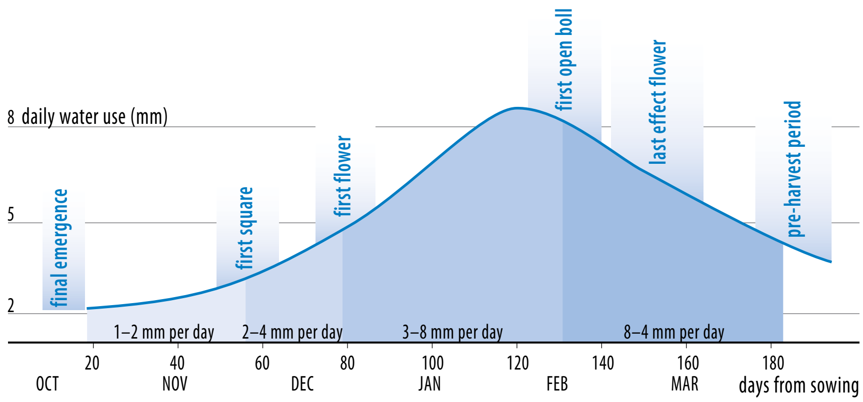
It should be noted that the method above uses standard crop coefficients which relate to crops under disease free, well fertilised, optimum soil moisture and full production conditions. Often crops do not meet these conditions, and the crop coefficient (K_c) can be varied under these circumstances to better reflect the actual crop conditions. However this may be difficult to do with accuracy, and usually involves at least some additional measurement, for example of leaf area index (LAI). Newly developed tools such as IrriSAT can use regular satellite imagery of the vigour of individual fields to provide an improved measure of K_c and hence ET_c.

Crop Water Use and Plant Growth

A crop's requirement for water changes throughout the growing season, following the pattern of evapotranspiration (Crop Water Use). The rate of evapotranspiration is determined primarily by meteorological factors and the availability of soil water. Total crop evapotranspiration will also vary with canopy size, or leaf area.

Using cotton as an example, the figure below shows that the period where crop leaf area peaks (3 to 5 weeks after the start of flowering) is also the time of maximum daily water use of between 8 and 10 mm (Figure 2.1.3).

Figure 2.1.3. Nominal seasonal Daily Water Use (mm/day) for cotton production.



The maximum demand for water also coincides with the growth period between peak flowering and early boll development. Exposing the plant to water stress at this stage of growth can result in significant yield reductions. The impact of water stress at different crop growth stages on final yield is directly related to the water demands expressed by the crop. Stress during periods of high water demand can produce large reductions in yield. Stress during peak flowering can double yield losses compared with early or late seasonal stress. The impact of any one stress period is increased if followed by further stress. Further information for cotton and grain crops can be found in chapters 3.1, 4.1, 4.2, 4.3 and 4.4.

The total seasonal crop evapotranspiration is an accumulation of the daily crop ET_C over the whole season. This figure will vary from crop to crop and from year to year, but will typically be within the range provided in Table 2.1.2.

Table 2.1.2. Water Requirements of Crops

Crop	Crop Evapotranspiration Requirement[1] (mm)	Peak Daily Water Use (mm/day)			Critical Irrigation Periods
		ET_0 = 6 mm	ET_0 = 8 mm	ET_0 = 10 mm	
Barley**	350 to 500	6.9	9.2		Shot – blade to late flowering
Chickpeas**	350 to 500	`6.0	8.0		4 to 5 weeks after flowering
Cotton***	650 to 770	6.9–7.2	9.2–9.6	11.5–12	Peak flowering and early boll development
Maize*	600 to 850	7.2	9.6	12	Tasselling through seed fill
Lucerne for hay**	750 to 1500	6.9	9.2	12	From one week after cutting to flowering
Navy beans**	300 to 450	6.9	9.2	11.5	Flowering
Peanut**	500 to 700	9.2	9.2	11.5	Flowering and pegging to pod maturity
Sorghum*	450 to 850	6.0–6.6	8.0–8.8	10–11	Boot to dough stage
Soybeans**	500 to 775	6.9	9.2	11.5	Flowering to leaf drop
Sunflower*	600 to 800	6.9	9.2	11.5	Once bud is visible, start of flowering and just after petal drop
Wheat**	350 to 500	6.9	9.2		Boot stage and flowering until soft dough stage

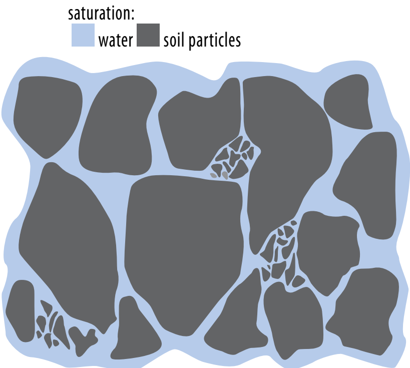
1. The crop evapotranspiration is the demand that must be met by in-season rainfall, irrigation and stored soil water at planting.

Sources: *Pacific Seeds 2006/07 Cropping yearbook. **Graham Harris, DPI&F, pers.comm. ***WATERpak 2001

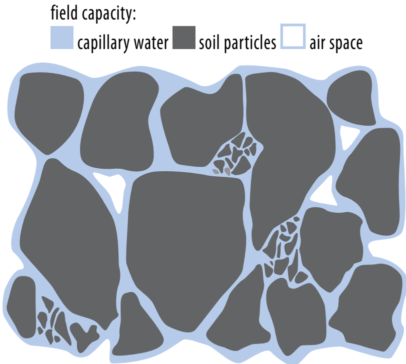
Understanding Soil Water

An understanding of basic soil water states is important for managing irrigation scheduling. Figure 2.1.4 illustrates the relationships between the terms described below.

Saturation may occur after heavy rain, during surface irrigation, or following over-irrigation. This is when even the largest pores are filled with water. When the soil is saturated, there is no air for the plant roots. This will stress many plants and is often described as waterlogging.



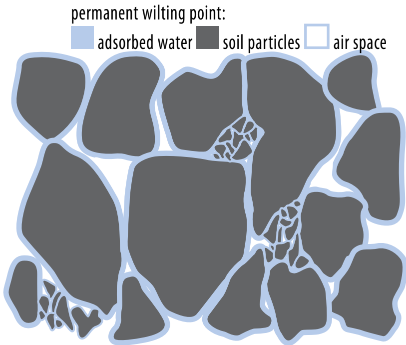
Field capacity (full point) occurs after large soil pores (macropores) have drained due to gravity. Depending on the type of soil, this drainage may take from a few hours up to several days. When the large pores have drained, the soil is still wet, but not saturated. The soil is said to be at field capacity. Field capacity in most soils is at a soil-water tension of about –8 kPa.



Refill Point (target deficit) is the point at which a particular crop finds it difficult to extract water from the soil and begins to stress, slowing crop growth. For most cotton and grain crops, this usually occurs when the soil water potential is between -60 and -100 kPa.

The refill point changes during the season. Young plants have small roots that only have access to a limited part of the soil profile. As the plant grows, the roots can access more of the profile and therefore tolerate a larger soil moisture deficit before reaching refill point. Determining the refill point can be achieved by measuring soil water potential or by analysing daily water use patterns to determine when the crop is finding it difficult to remove water. If irrigation is not applied prior to soil water levels passing an accurate refill point, then a yield reduction will occur, depending on the stage of the crop.

Permanent Wilting Point occurs when the soil reaches a point where the plant can no longer extract moisture. Once the soil has passed this point, water is held by the soil so tightly that the plant cannot extract it and will start to die.



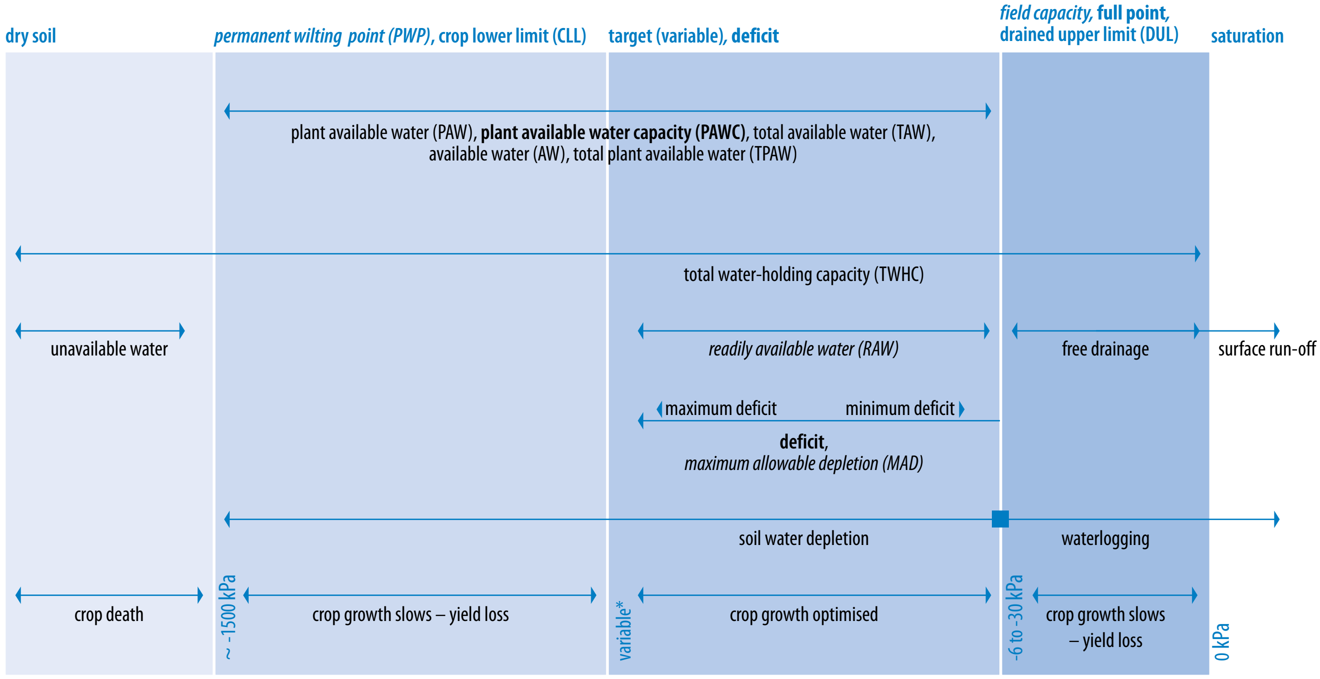
A note on deficit

The term deficit is often used in two ways:

1. It most often used to describe the current moisture status of the soil. In this usage, it suggests how much water would be required to fill the profile to the full point.

2. Deficit is sometimes also used interchangeably with the term Refill Point. This usage would be more appropriately termed Target Deficit as it is the deficit at which plant stress, and hence irrigation, is triggered.

Figure 2.1.4. Soil water terminology



Terms in *italics* are nationally adopted (ANCID); current cotton industry terms are in **bold**.

Units can be kPa, mm or percentage volumetric soil water (% VSW), depending on soil water measurement method.

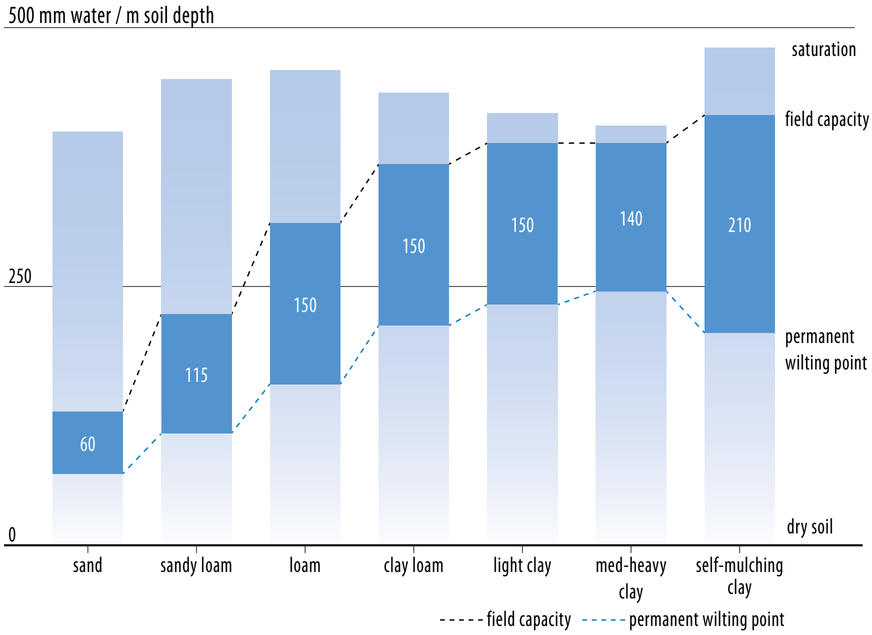
* variable suction levels depending on soil type and management

Source: David Williams

Most soils have a similar total water holding capacity, generally between 400 500 mm per metre depth of soil, as illustrated in Figure 2.1.5. However, the amount of water actually available for use by the plant varies greatly due to different soil textures and their influence on soil moisture.

The shaded section in the middle of each column shows the average amount of water available to plants. Water held below permanent wilting point is shown by the bottom section of each column, and free-draining water (above field capacity) is shown in the top section.

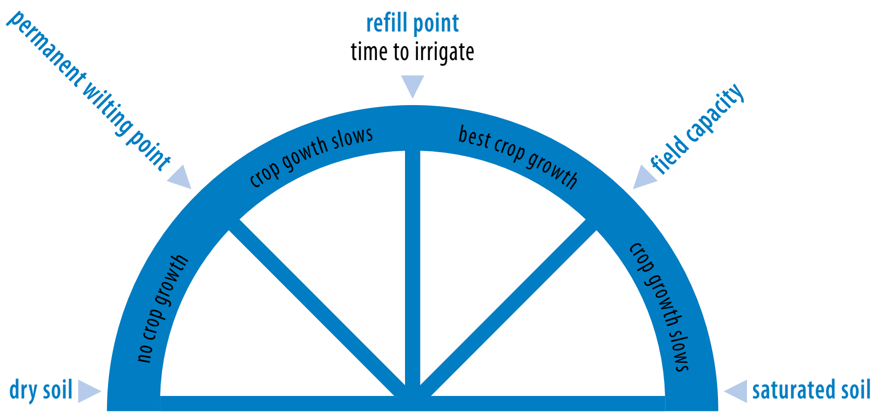
Figure 2.1.5. Total amount of water held in different soils



Plant Available Water Capacity (PAWC)

The amount of water held in the soil between field capacity and the permanent wilting point represents the Plant Available Water Capacity (PAWC). However irrigation scheduling decisions should be undertaken when the soil moisture is between the full and refill points, known as the Readily Available Water (RAW). This can be visualised like a fuel gauge as in Figure 2.1.6.

Figure 2.1.6. Soil Water '*Fuel Gauge*'



Scheduling Irrigations

Irrigation scheduling is the decision of when and how much water to apply to an irrigated crop to maximise crop productivity. Good scheduling should provide plants with water that is within a desired range and should limit over or under irrigation.

The advantages of irrigation scheduling include:

- The management of water between fields to minimise crop water stress and maximise productivity.
- Improvements in energy, water and labour efficiency through more effective irrigation.
- An increase in Water Use Efficiency and fertiliser effectiveness through reduced surface runoff and deep drainage.
- Increased net returns through increased yields and improved crop quality.
- A minimisation of water-logging problems.
- Assisting control of root zone salinity problems through controlled leaching.
- Additional crops through savings in irrigation water.
- The ability to precisely control availability of soil moisture when using precision application techniques.

It is very important to remember that irrigation scheduling is strongly related to system performance. Therefore system efficiency and uniformity should be taken into account when making irrigation scheduling decisions.

The following section will outline a number of methods for scheduling irrigations and will focus on the tools available and how these are used. It should be noted that a range of other factors should also be considered when scheduling an irrigation including;

- Total water availability (WATERpak Chapters 2.2, 3.3)
- Crop growth status and potential yield (WATERpak Chapters 3.1, 4.1, 4.2, 4.3, 4.4)
- Predicted rainfall and future temperatures (WATERpak Chapter 2.3)
- Practical farm management logistics such as the physical movement of water

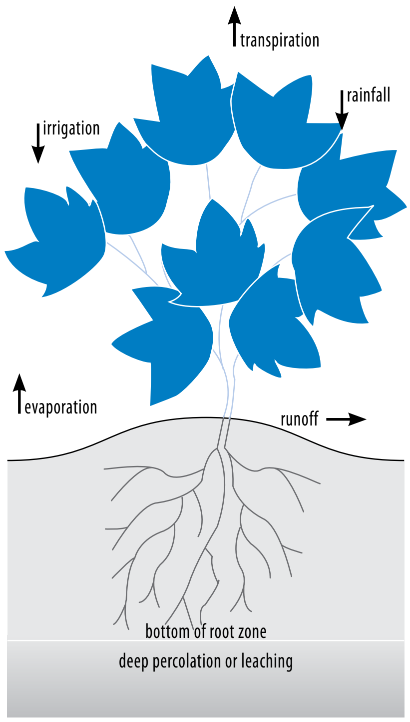
Scheduling methods & tools

ET Based Methods

Crop evapotranspiration is calculated from climatic factors and crop coefficients as described above. This data can be used for daily accounting of the amounts of water entering and leaving the crop root zone.

This procedure is based on estimating the soil water content in the crop root zone by balancing the water inputs and outputs, as illustrated in Figure 2.1.7.

Figure 2.1.7. Soil water balance in irrigated cropping systems (courtesy of Colorado State University, USA).



Irrigation and rainfall add water to the root zone. Some of this water may be lost as runoff or drainage below the root zone. Conversely, in some situations water can also enter the root zone from a high water table or lateral water movement through the soil. Water is also lost from the root zone through evapotranspiration.

The current soil moisture deficit can be calculated on a daily basis to indicate when the amount of water in the root zone is insufficient, suggesting that irrigation should be applied.

Deficit (today) = Deficit (yesterday) – irrigation – rainfall + ET_c

Where:

Deficit = soil moisture deficit (amount of available water in the root zone below field capacity)

ET_c = Crop evapotranspiration (crop water use)

Irrigation and rainfall figures have already had runoff and drainage taken into account

Note: we are using soil moisture deficit in this calculation, as that is the terminology that is most often used throughout the industry. The concept of deficit must be understood: as the deficit increases, the amount of water in the soil is less. Adding water to the soil (e.g. irrigation) reduces the deficit, bringing it closer to zero. A Deficit of zero indicates the soil cannot hold any more water.

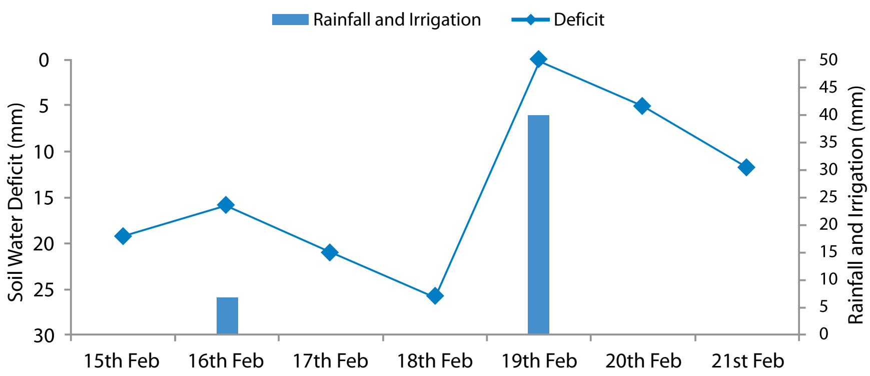
Example:

We will use the ET_c data for the soybean crop illustrated above. The items required to perform the calculations have been placed in the table below. Following the logic above:

Deficit (today) = Deficit (yesterday) – irrigation – rainfall + ET_c

or, Column 6 = Col 2 – Col 3 – Col 4 + Col 5

1	2	3	4	5	6
Date	Deficit (yesterday) (mm)	Irrigation (mm)	Rainfall (mm)	Crop Water Use (ET_c) (mm)	Deficit (today) (mm)
15 Feb	14			5.3	19.3
16 Feb	19.3		7	3.6	15.9
17 Feb	15.9			5.1	21
18 Feb	21			4.8	25.8
19 Feb	25.8	40		6.3	0 (–7.9)
20 Feb	0			5.1	5.1
21 Feb	5.1			6.6	11.7



In this example we can see that on most days, the soil water deficit increases due to crop water use. A small rainfall event on February 16th corresponds with a lower ET_c value, with the net effect being a slight replenishment of soil moisture. On February 19th an irrigation event takes place, with the amount applied (40mm) greater than the current soil water deficit. As the soil is full of water when the deficit is zero, additional water is lost as runoff or drainage and this amount (7.9mm) is removed from the calculation and the deficit manually set to zero.

As discussed in the previous section on Evapotranspiration, ET_c is determined from available ET_o data by applying appropriate crop coefficients. It follows that poorly selected crop coefficients will result in inaccurate ET_c and corresponding errors in the soil water balance calculations. A recently developed tool, IrriSAT, regularly obtains NDVI (Normalised Difference Vegetation Index) data from satellite imagery (refer to WATERpak chapter 2.3).

This data can then be used to determine much more accurate crop coefficients and hence improve the accuracy of ET_c. IrriSAT uses this data to automatically calculate the soil water balance in a similar process to that described above.

Plant Based Methods

Whilst calculations of soil moisture can infer the likelihood of crop stress, direct observation of the crop can reveal the actual level of stress being experienced. Visual signs of water stress may include wilting, fruit drop and death in sections of the crop. However these signs often occur after stress has been present for some time, and are of limited use in accurate irrigation scheduling.

Furthermore, plant indicators may not necessarily be a result of water stress, but of other causes such as heat, salinity or nutritional deficiencies. For example, some plants roll their leaves up in response to an extremely hot, windy day - referred to as Midday Wilt in cotton. Other plants only show wilting when water is severely limited. These crops move into a "shut-down" phase which can impact yield depending on crop development stage at which this occurs. Other plants will wilt in response to water logging or root disease.

Whilst simple visual indicators are of restricted use for irrigation scheduling, more technologically advanced methods of plant monitoring can provide highly accurate responses to small changes in plant stress levels. In the past, these methods have often been costly and complicated, with use predominantly restricted to research.

Plant based scheduling tools can be classified as either contact or non-contact depending upon whether they have to come into physical contact with the plant.

Contact sensors typically provide point source data, with multiple sensors required wherever instrumentation is left in-situ to provide time series data. Contact sensors may be either destructive (pressure bomb) or non-destructive (sap flow, stem diameter).

Point source measurements typically record data for only a single plant; hence the way in which this plant represents the rest of the field is very important. This issue is the same for point source soil moisture measurements.

Non-contact sensors do not come into contact with the plant and usually can be used to measure numerous points across a number of fields, or even entire fields at once. Cloud cover can be a major influence as airborne and satellite sensors must be able to view the field, whilst ground level and hand held sensors usually require clear conditions to provide meaningful data.

On the whole, most plant based sensors are not yet practical for wide spread use, or do not yet offer significant advantages over other existing scheduling techniques. This may improve in the future as further research and development occurs.

Soil based methods

Measurement of soil moisture characteristics allows us to infer the likely stress that a plant may be undergoing. There are three main measurement types for determining the availability of water in the soil.

- Gravimetric – the amount of water in the soil based on weight. This is calculated by oven drying soil samples to find the difference between their wet and dry weight. This measure is of little use for scheduling due to the difference in density of different soils and the time taken to obtain measurements.
- Volumetric – the amount of water in the soil based on volume (cm^3/cm^3). This is the most common way of expressing soil moisture, usually in mm of water per depth of soil (e.g. 300mm of water per 1m of soil = 30% Soil Moisture). A number of tools use different water properties (electrical conductivity, neutron scattering) to infer the volumetric water content. A truly accurate measure requires calculation of soil bulk density.
- Soil Water Potential – measures the soil suction (pressure) and is the measure that most accurately relates to actual plant stress. The soil water potential indicates how difficult it is for a plant to remove water from the soil.

Volumetric measurements of soil moisture have become popular as they enable an irrigator to relate the volume of water required to refill the soil profile (deficit) to the amount of water applied in an irrigation event. However to achieve this with accuracy, additional information is required such as the volumetric moisture content at field capacity and refill point. This information is obtained from physical soil tests which are often time consuming to obtain. Therefore analysis of volumetric soil moisture data is often undertaken using uncalibrated data by looking at trends in daily water use.

On the other hand, measures of soil water potential can directly indicate how difficult it is for a crop to extract moisture from the soil. Thresholds of suction at which crops are able to readily extract water are generally well known, therefore a single measurement can indicate whether an irrigation is required or not. However as the information is not volumetric, determining how much water should be applied, or how long it will take to deplete the existing soil water reserves is more difficult.

A Note on Calibration:

It must be noted that neither capacitance probes nor neutron probes provide a true measure of volumetric moisture content without site specific calibration. However for general irrigation scheduling practice, accurate measurements are not required as the trend in soil water extraction and relative differences in soil moisture are sufficient. Further information is available in Chapter 2.7

Plant Based Monitoring Tools Available

Advantages	Disadvantages	Comments
Plant Based Monitoring Tool: Stem water potential *Specifications:* A pressure chamber measures the water potential of a non-transpiring leaf		
More robust than leaf water potential Relatively cheap	Destructive measurement Requires a lot of practice to make reliable measurement Point source measurement – many points required for representative sample No continuous data – new measurements Required each time.	Need more testing to determine critical levels. Research tool.
Plant Based Monitoring Tool: Canopy temperature (including thermography) *Specifications:Infra-red thermometers (IRTs) including handheld IR guns, continuous wireless fixed sensors, aerial/ground rig attached sensors and thermal imaging cameras.*		
Strong relationship between canopy temperature and plant water status, irrigation scheduling possible to maintain crop at thermal optimum (e.g. BIOTIC) Relatively cheaper wireless technology with continuous monitoring capabilities being developed Non destructive measurement Automation possible Can get a picture of whole field or many points within field Using cameras or remote sensors, many fields can be measured with a single instrument	Errors can occur if background (soil) temperatures are being measured in the field of view of the instrument Point source measurement using hand held or fixed sensors Variations in temperature depending on the part of canopy and angle of measurement Data interpretation can be difficult as both water stress and ambient conditions (air temperature, radiation, humidity, wind speed etc) influence changes in canopy temperature. Thermograph can be expensive Readings need to take ambient conditions into account Continuous measurements can result in large data sets that can be difficult to manage and interpret.	Need more testing for irrigation scheduling in Australian systems May have potential for non-point source data collection, but not yet commercially practical.
Plant Based Monitoring Tool: Leaf Water Potential *Specifications:* A pressure chamber measures the leaf water potential of a transpiring leaf.		
A classic, standard measurement Equipment relatively cheap	Destructive measurement Requires a lot of practice to make a reliable measurement. Time/conditions of day dependent for consistency over time Point source measurement No continuous data – new measurements required each time.	Research tool
Plant Based Monitoring Tool: Plant growth measurements *Specifications:* A range of plant growth technologies including stem and fruit diameter sensors		
Relatively cheap Easier for grower or consultant gives continuous data	Not accurate in all situations Additional measurements required Point source measurement - multiple sensors required	Plant growth measurements will likely provide similar function of trend analysis as current soil moisture monitoring.
Plant Based Monitoring Tool: Satellite Imagery and remote sensing of crop water stress *Specifications:* Spectral data and images of varying characteristics, resolution and coverage		
Applications are wide ranging	Accuracy is uncertain Ground truthing can be expensive	IrriSAT is a new tool which uses remotely sensed data to improve ET_c calculations. Mobile, low altitude sensors may provide a better resolution and improve application.

Source: Modified from CRC for Irrigation Futures

Soil Moisture Monitoring Tools Available

<table>
<tr><th>Advantages</th><th>Disadvantages</th><th>Overall</th></tr>
<tr><td colspan="3">Soil Moisture Monitoring Tool: Capacitance probes – stationary (C-probe, Enviroscan, Buddy, Profile Probe, Theta Probe, ECH20, etc.)
Specifications:
Type of sensing – capacitance
Type of reading – volumetric (often uncalibrated)
How does it work? By measuring the dielectric constant of the soil. The amount of water in the soil is related to its ability to transmit electromagnetic waves or pulses</td></tr>
<tr><td>Continuous logging
Remote access
Multiple access tubes to one logger
Gives indication of variation in crop water use on a daily basis</td><td>10 cm diameter reading zone is reasonably small
Cracking soils can effect soil moisture reading
Generic calibrations give poor estimate of total water content
Some models have cables from access tube to logger
Unit is stationary so number of sites limited</td><td>Suitable tool for growers, be aware of issues on cracking soils.
Expensive but gives detailed soil moisture record.</td></tr>
<tr><td colspan="3">Soil Moisture Monitoring Tool: Neutron Probe
Specifications:
Type of sensing – radioactive
Type of reading – volumetric (often uncalibrated)
How does it work? The radioactive source emits neutrons which are slowed down by collision with hydrogen in water molecules. The number of slow returning neutrons measured is related to the amount of water in the soil</td></tr>
<tr><td>Large reading zone (average diameter 30 cm) is beneficial in cracking soils
Predictive Software
Portable, multiple access tubes
Usually more accurate than most other volumetric sensors</td><td>Require a license to use the probe and approved transport and storage facilities.
Manual data collection
Data reading of each access tube is time consuming
No remote access or continuous logging
Soil specific calibrations required for accurate readings
Regular readings required for comprehensive date set and to identify trends.
Reasonably heavy and expensive instrument.
Radioactive source must be properly disposed of.</td><td>Most accurate for clay soils
Need to be licensed due to radioactive hazard</td></tr>
<tr><td colspan="3">Soil Moisture Monitoring Tool: Capacitance probe – portable (Diviner 2000, Gopher, Aquaterr, Profile Probe, Theta Probe, etc.)
Specifications:
Type of sensing – capacitance
Type of reading – volumetric</td></tr>
<tr><td>Quicker read than neutron probe
Readout in-field
Can determine change in daily water use from output graphs if readings are frequent
Portable, multiple access tubes.
Reasonably inexpensive</td><td>Small (10 cm diameter) reading zone
Cracking soils will effect soil moisture reading
Generic calibrations give poor estimate of total water content
Absolute numbers obtained are of little value without calibration
Frequent readings required to identify trends.</td><td></td></tr>
<tr><td colspan="3">Soil Moisture Monitoring Tool: Porous media (tensiometers, gypsum blocks, matrix sensors, etc.)
Specifications:
Type of sensing – pressure (suction)
Type of reading – soil water potential
How does it work? Porous media (gypsum, ceramic, etc) allows water to flow from soil. Pressure sensor within the device measures suction directly.</td></tr>
<tr><td>Cheap
Gives direct reading of when to irrigate
Calibration is usually unnecessary
Many products can be logged to provide time series data</td><td>Some products may not work well in very wet or very dry soil
Does not give an indication of the volume of irrigation required
Permanent installation of block devices not well suited to field crops
Some products may not respond quickly to change in moisture content</td><td>Only devices to give a direct reading of how difficult it is to extract water from the soil regardless of soil type.</td></tr>
</table>

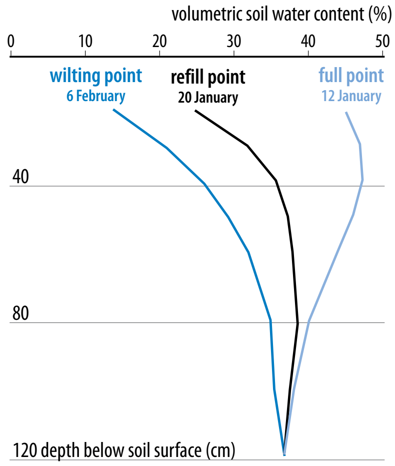
Source: RWUE3 2007

Analysing Soil Moisture Probe Data

Data from soil moisture probes will generally be presented in one of two ways::

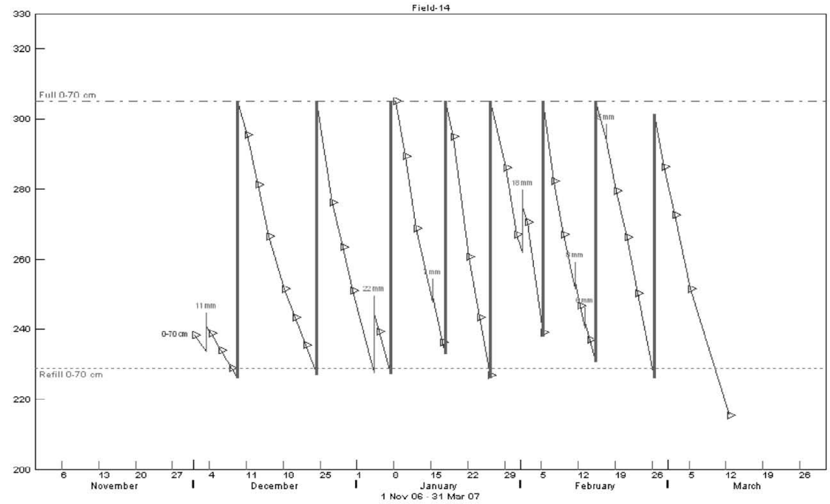
1. Non-continuous data (obtained from manual recording devices such as **Neutron probes** or **Diviners**) is often presented as a graph of soil depth vs. moisture content (Figure 2.1.8). Each line on the graph represents a reading taken at a different time.

Figure 2.1.8. Soil moisture data presentation typical of manual measurement devices (e.g. NMM)



However, data may also be represented as a graph of moisture vs. time for the total of the whole profile (Figure 2.1.9). This graph is usually most useful if readings are taken regularly.

Figure 2.1.9. Presenting non-continuous soil moisture data over time

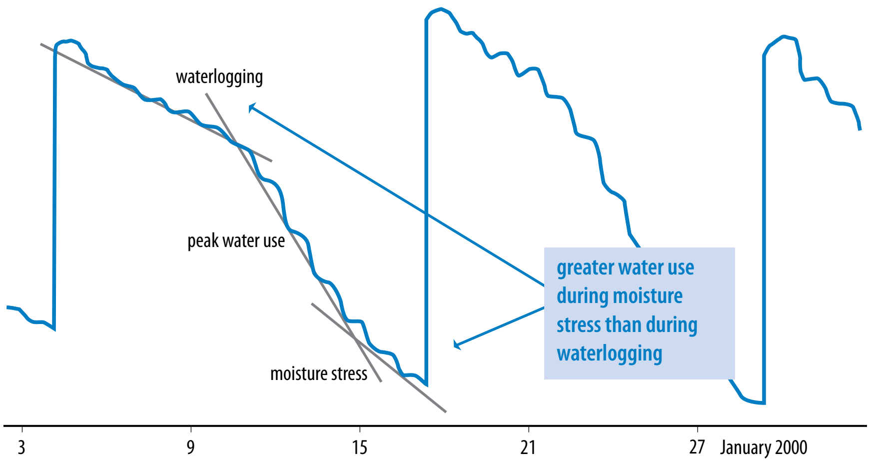


RootZone	Full	REFILL	Previous	Current	Deficit	Probe Dwu	Pdwu Date	EDWU	Date	Amount
0-70 cm	305 mm	229 mm	252 mm	216 mm	90 mm	4.9 mm/day	26 Jun	4.3 mm/day	26 06 16:20	76 mm

2. Capacitance probe data is typically presented as a graph of moisture content vs. time (Figure 2.1.10.). The line(s) on the graph can either represent a sum (total) of all soil moisture readings within the entire profile (summed graph) or each line may represent the moisture reading at a different depth in the soil profile (stacked graph).

*Note that data from either device may be presented in either fashion.

Figure 2.1.10. Soil moisture data presentation typical of continuous logging devices



Source: Sloane 2003

How to schedule an irrigation using soil moisture data

In irrigation scheduling, soil moisture data is used as a proxy for plant stress. In other words, a certain level of soil moisture deficit is chosen as the point at which the crop starts to suffer from stress due to insufficient water availability. Figure 2.1.8. demonstrated a typical presentation of non-continuous soil moisture data, but also shows the typical root extraction patterns for a cotton crop for the full, refill and wilting points. Crops will start to stress (with potential yield reduction) when they reach the refill point and will die when they reach the wilting point. Crops typically use most soil moisture in the top of the soil profile and proportionally less, deeper in the profile. Moisture is generally obtained from the top of the profile first, although on some occasions this may not occur. For example a rainfall event may cause temporary waterlogging at the soil surface whilst water extraction continues at depth.

The full point (field capacity) occurs when the soil profile is full of water and no drainage is evident. It can usually be determined by taking a soil moisture reading of the profile 1-2 days after a surface irrigation event or after a large rain event. In most cases this point is quite easily identified, particularly from continuous soil moisture data. It should be noted that although most surface irrigation events completely fill the soil profile, this is not always the case, and is almost never the case with drip or CPLM irrigation systems. In these cases, the full point may only be evident after large rainfall events.

The refill point. If an irrigation is not applied prior to soil water levels passing the refill point, then a yield reduction will occur depending on the stage of the crop. However determining the refill point with accuracy can be difficult. In part, this is because the refill point changes during the seasons. Young plants have small roots that only have access to a limited part of the soil profile. As the plant grows, the roots can access more of the profile and therefore tolerate a larger soil moisture deficit before reaching refill point. Determining an appropriate refill point using soil moisture data requires some trial and error, and is open to interpretation as no real measure of plant stress (e.g. leaf water potential) is used. The process involves examining the daily water use figures of the crop. Once the daily water use starts dropping this is a sign that the crop is experiencing difficulty getting water and the crop has reached (or passed) the refill point.

Daily crop water use will vary depending upon the weather conditions for each day (evaporative demand) as well as the difficulty with which the crop can extract moisture from the soil. Figure 2.1.10. shows how the crop daily water use can change when the plant is stressed through either waterlogging or moisture stress. When a crop reaches the refill point and moisture stress starts to occur, the daily water use declines.

Remember that uncalibrated probes do not give absolute measures of soil moisture. This means that you cannot simply take a reading of soil moisture and compare it to a refill point determined from physical soil sampling. For manual (portable) probes there are a couple of options:

- Take readings regularly (every 2 or 3 days) as well as before and after irrigations and rainfall events. This will give enough data to perform some basic trend analysis as described below.
- Use historical data. Provided you have data for a number of previous seasons, and ensuring you have enough access tubes to average out individual readings, it is possible to reduce the frequency of manual readings. Be cautious of this method where soil properties are likely to change significantly due to compaction, ripping or extended drying

Frequent manual readings or data collected using a continuous logging device can be used to deduce a refill point based upon trends in water extraction over time. As indicated in Figure 2.1.10., water extraction patterns are stepped on a daily basis, being flat at night (little or no water use) with a rapid decline during the day. The overall slope indicates how readily extraction is occurring:

- Steep slope - high water use
- Flat slope - water logging or stress

Care should be taken not to confuse a drop in daily water use caused by cloudy weather. If you have daily water use data for an entire season and want to standardize them for changes in the weather, it is possible to do this by dividing the DWU figure by either solar radiation data or air temperature data from a weather station.To schedule irrigations from soil moisture data it is important to know:

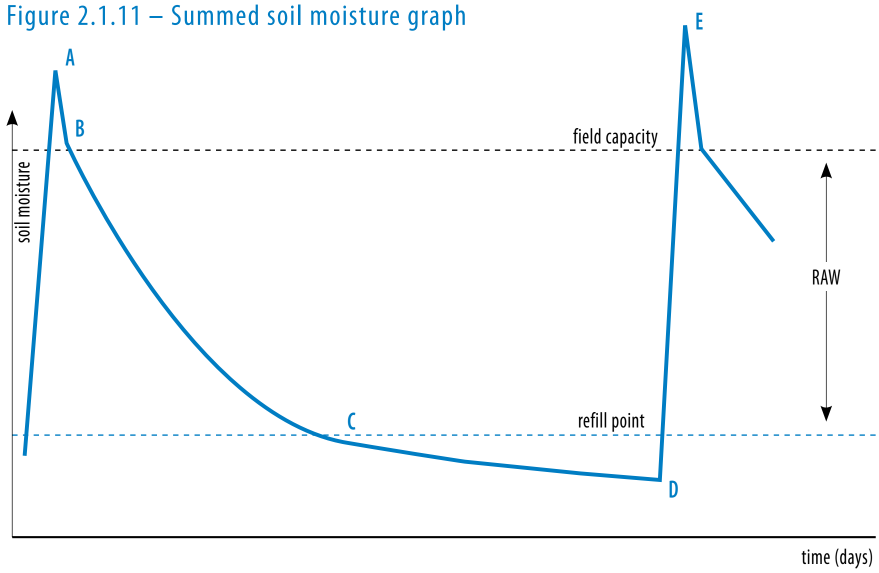
Use of the summed graph

The summed graph displays total soil moisture for the probe depth (typically 1 metre). It is useful as a 'quick reference' of soil moisture or to indicate irrigation when the refill point has already been determined. It can be used to determine field capacity (full point), but determining refill point can be more difficult because once water extraction in the summed graph has started to decline, the crop is already under stress.

Figure 2.1.11 shows a summed soil moisture graph, illustrating differences in water use over time.

- In this figure, the soil has been irrigated, becoming saturated (A).
- After irrigation ceases, soil water drains due to gravity until field capacity is reached (B). This can occur quite quickly, as illustrated here, or may take a number of days causing waterlogging (as in Figure 2.1.10).
- Under optimal conditions, the plant extracts water freely, until the refill point is reached and crop stress occurs (C).
- In this case, irrigation has been delayed and the crop has been stressed until irrigation occurs (D)

Figure 2.1.11 – Summed soil moisture graph

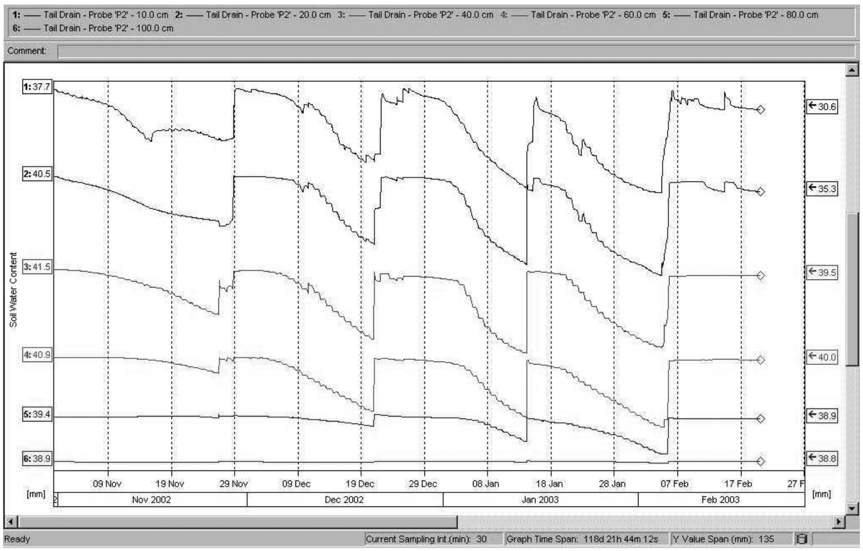


The refill point is clearly evident in this figure (at C), but by the time the decline in water use can be confirmed, water stress has started to occur. Analysing extraction patterns at different depths can help to improve the prediction of refill point.

Use of the stacked Graph

The stacked graph displays soil moisture at each sensor depth, which is useful for determining refill points and examining extraction patterns. Figure 2.1.12. shows a stacked soil moisture graph, illustrating differences in the amount of water used at different depths.

Figure 2.1.12. – Stacked soil moisture graph



A stacked graph is helpful to predict an appropriate refill point. Because a plant will typically extract water from closer to the surface first, the sensors close to the surface will show a decline in daily water use before the crop is under stress, as it is still accessing plentiful water at lower depths.

For most crops with an effective rootzone of around 1 metre, you can determine the refill point by analysing the trend of sensors at 40, 50 or 60cm, depending upon local conditions. Often a slowing of water extraction at this depth indicates that the plant is about to stress as it will have more difficulty accessing water from deeper in the profile.

It may be possible to determine when this slowing occurs through visual inspection of the graph, or the data can usually be viewed or exported so that the actual daily water use figures can be inspected. Don't forget that for an uncalibrated probe, these daily water use figures do not accurately represent the actual amount of water used by the plant in a day.

Soil Moisture Probe Placement

The correct site and installation of access tubes is critical for soil moisture monitoring tools as only a small amount of soil is sampled. Therefore, the position needs to be representative of crop type, density and vigour, soil type, irrigation system uniformity and application. Probes need to be out of the way of machinery, so they are usually placed in the centre of plant line. However in some situations, for example in skip row crops, there may be an advantage in measuring soil moisture in other locations.

A number of different techniques can be used to ensure probes are placed in a representative area of the field. Electromagnetic induction (EM) surveys can provide an estimate of soil properties such as clay content, salinity and moisture content. This data can be used in conjunction with maps of field topography, previous yield and crop vigour to determine an appropriate site for moisture probes to be placed. Further information is included in this article.

Soil compaction and its impact on setting refill points

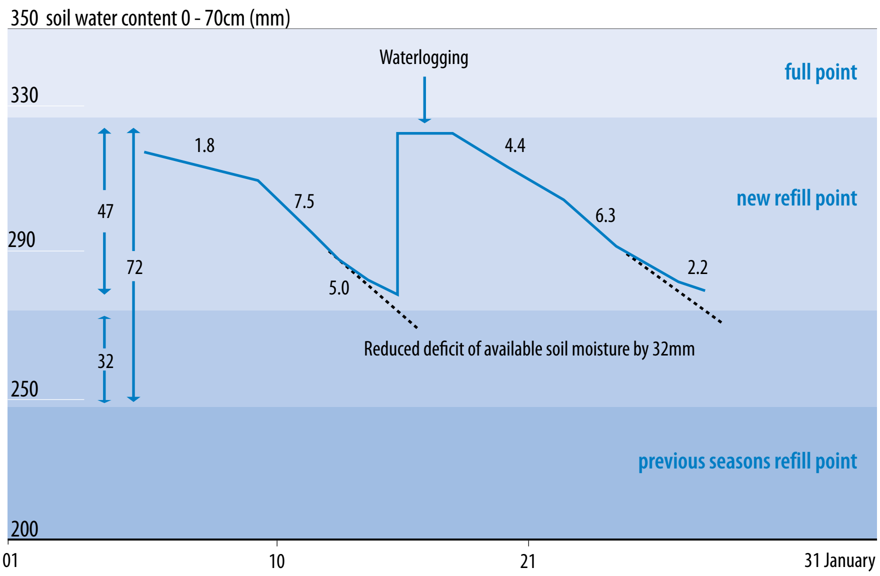
This example demonstrates how a wet pick in the previous season influences the setting of refill points the following season. A deficit of 80-90 mm is typical for heavy clay soils around Moree, which have good soil structure. Frequent soil water readings (2-3 times per week) enable the daily water use of the crop to be determined. The daily water use will decline assuming constant weather conditions, when the refill point has been reached.

Figure 2.1.13. shows, following the second crop irrigation on 2/1, a low daily water use (1.3 mm and 1.8 mm) is evident on 5/1 and 9/1 due to water logging and cool temperatures. On 11/1 the water use was 7.5 mm/day. The daily water use then dropped to 5.0 mm/day and it was decided to irrigate this crop again, at a deficit of 49 mm. This decision was based on crop symptoms and a lower than normal (7.5mm) daily water use at a deficit of 49 mm. A similar pattern of water use was evident between the third and fourth crop irrigations. Between 14/1 and 16/1 a daily water use of 0.0 mm/day was recorded due to waterlogging. This increased to 4.4 mm/day as the crop recovered from the waterlogging to a peak of 6.3 mm/day on 22/1. By 25/1 the daily water use had dropped to 2.2 mm/day at a deficit of 47 mm.

This is a similar deficit to the previous irrigation, indicating that the refill point had changed from a deficit of 79 mm which it was in the previous season to a deficit of 47 mm. Wet picking reduced the deficit by 32 mm in one season due to soil compaction (Figure 2.1.13). This reduces the interval between irrigations from about 14 days to 8 days.

Careful monitoring of the crop's daily water use and root extraction patterns as well as crop observations enables refill points to be set correctly.

Figure 2.1.13. : The effect of soil compaction on soil moisture availability



References

Allen, RG , Pereira, LS , Raes, D and Smith, M 1998, Crop evapotranspiration: guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper No. 56, Rome.

Available http://www.fao.org/docrep/X0490E/x0490e00.htm, accessed 14 June 2007.

Harris, G. Irrigation Water balance Scheduling, 2001. DPI&F Fact Note

Harris,G. WATER REQUIREMENTS OF CROPS. DPI&F Fact Note, Inglewood.

Meyer, R., Belshe, D., O'Brien, D. and Darling, R. (1999) High Plains Sunflower Production Handbook, North Dakota State University, Cooperative Extension Service

Pacific Seeds Variety Guide 2006/07. Pacific Seeds Head Office, Anzac Avenue, Toowoomba. www.pacificseeds.com.au

Paul E Dodds, Wayne S Meyer and Annette Barton. A Review of Methods to Estimate Irrigated Reference Crop Evapotranspiration across Australia. CRC for Irrigation Futures Technical Report No. 04/05. April 2005. www.irrigationfutures.org.au/imagesDB/news/CropEvapotranspirationCRCIFTR042005.pdf

Sloane, D. Using C-probes – Irrigation decisions from the Plants Perspective. Australian Cotton Grower Vol25, no.4 August – September 2004