2024

IrriSAT Technical Reference v2

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Citation Details:

Hornbuckle, J., Vleeshouwer, J., Ballester, C., Montgomery, J., Hoogers, R., Bridgart, R. Filev Maia, R. & Tondato De Faria, B. (2024) IrriSAT Technical Reference v2, Deakin University, Hanwood, NSW, Australia. P. 17

This document is updated from the original:

Hornbuckle, J., Vleeshouwer, J., Ballester, C., Montgomery, J., Hoogers, R. & Bridgart, R. (2016) IrriSAT Technical Reference, Deakin University, Hanwood, NSW, Australia. P. 17

Executive Summary

IrriSAT is a decision support tool to assist irrigators with irrigation water management. The IrriSAT methodology aims to be as simple as possible (in order to limit the number of inputs and parameters required), yet sufficiently complex to accurately estimate irrigation requirements. The IrriSAT methodology described in this document can be summarised as follows:

- The water balance approach to irrigation scheduling keeps track of the soil water deficit by accounting for all water additions and subtractions from the soil root zone on a daily basis.
- The IrriSAT methodology uses a simplified approach whereby: $\Delta S = P + I - ET_c$. This approach assumes crop water consumption (or evapotranspiration) accounts for the biggest subtraction of water from the soil root zone while precipitation and irrigation provide the major additions.
- The soil in the root zone has an upper limit of storing water that can be used by crops. This upper limit is constrained to the field capacity.
- As the crop grows and extracts water from the soil to satisfy its water use requirement (ET_c), the stored soil water is gradually depleted.
- ET_c is estimated using field observations and nearby climate observations.
- Crop reference evapotranspiration (ET_0) is estimated using the FAO Penmen Monteith Tall-Crop (alfalfa) reference using observations obtained from weather stations.
- Crop coefficients (K_c) are estimated by directly observing the crop growth on fields using remote sensing techniques. Strong relationships between NDVI and K_c can be used to achieve this.
- Tracking the water balance deficit in the root zone allows for a refill point to be defined which indicates when irrigation is required.
- Common metrics which can be used to measure the agronomic performance over a growing season include: the irrigation water use index (IWUI); crop water use index (CWUI); and gross production water use index (GPWUI).

Table of Contents

List of Acronyms

CWUI	Crop Water Use Index
ET	Evapotranspiration
FAO	Food and Agricultural Organization
fc	Field Capacity
GPWUI	Gross Production Water Use Index
IWUI	Irrigation Water Use Index
MAX	Maximum
MIN	Minimum
NDVI	Normalized Difference Vegetation Index
NIR	Near-Infrared Spectrum
PM	Penman-Monteith
pwp	Permanent Wilting Point
RAW	Readily Available Water
R	Red Spectrum
SWD	Soil Water Deficit
TAW	Total Available Water
WUE	Water Use Efficiency

List of Symbols

Roman Symbols

CR	capillary rise [mm]
C_n	numerator constant [-]
C_d	denominator constant [-]
DP	deep percolation [mm]
e_a	actual vapor pressure [kPa]
e_s	saturation vapor pressure [kPa]
E	evaporation [mm]
ET_0	reference evapotranspiration [mm]
ET_c	crop evapotranspiration [mm]
$ET_{c,d}$	crop evapotranspiration for day d [mm]
G	soil heat flux density [MJ m^2 day^{-1}]
I	irrigation [mm]
$I.S.W.D$	initial soil water deficit [mm]
I_d	irrigation for day d [mm]
K_c	crop coefficient [-]
$K_{c,i}$	the crop coefficient for a crop image pixel [-]
$K_{c,field}$	the arithmetic mean crop coefficient for a crop field [-]
P	rainfall [mm]
P_d	rainfall for day d [mm]
R_n	net radiation at the crop surface
RO	surface runoff [mm]
SWD_d	soil water deficit for day d [mm]
SWD_{d-1}	soil water deficit for the day prior to d [mm]
T	transpiration [mm]
T_a	air temperature at 2 m height [˚C]
U_2	wind speed at 2 m height [m s^{-1}]
W_{in}	water input to a system [mm]
W_{out}	water output from a system [mm]

Greek Symbols

Δ	slope vapor pressure curve [kPa $˚C^{-1}$]
ΔS	change in soil water storage [mm]
ΔSF	change in subsurface flow [mm]
ΔW	change in soil water volume within a system [mm]
Υ	psychometric constant [kPa $˚C^{-1}$]

The Water Balance Model

In order to control the quantity and availability of soil moisture to a crop, a soil water balance is used to model the quantitative water dynamics within the soil. The water balance is a statement of the law of conservation of matter, stating that matter can neither be created nor destroyed but can only change from one state or location to another. All water added to, subtracted from, and stored within a given volume of soil during a given period of time can be defined as:

$$\Delta W = W_{in} - W_{out} \qquad \text{eq (1)}$$

Where:

ΔW	change in soil water volume within a system [mm]
W_{in}	water input to a system [mm]
W_{out}	water output from a system [mm]

Figure 1 (Allen et al 1998) provides a diagram of a full water balance for a unit of soil. Inputs to this water balance consist of water inputs to the soil (irrigation, rainfall, subsurface inflow and capillary rise) and outputs which remove water from the soil (evaporation, transpiration, runoff, subsurface outflow and deep percolation).

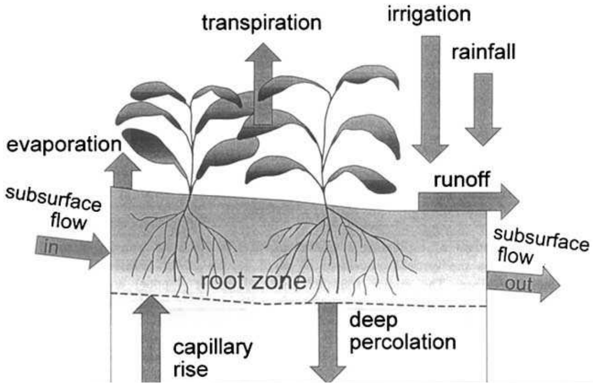

Figure 1: Conceptual full water balance model showing inputs and outputs, Allen et al. (1998)

The full water balance can be described at the soil root zone as:

$$\Delta S = P + I - T - E - RO - DP + CR \pm \Delta SF \quad \text{eq (2)}$$

Where:

ΔS	change in soil water storage [mm]
P	rainfall [mm]
I	irrigation [mm]
T	transpiration [mm]
E	evaporation [mm]
RO	surface runoff [mm]
DP	deep percolation [mm]
CR	capillary rise [mm]
ΔSF	change in subsurface flow [mm]

Simplifying the Water Balance

The IrriSAT water balance model is a simple approach to tracking water deficit in the soil root zone. It further simplifies the water balance described in eq (2) by making the assumption that subsurface flow in and out are generally negligible (consistent with flat irrigated fields found extensively across the major irrigated areas). Capillary rise is assumed negligible, which would be the case with a water table deep below the soil surface and efficient irrigation practices. In certain irrigation situations these assumptions may not be met so it is important to understand the particular circumstance in terms of how this approach represents these situations. If for instance you have significant deep drainage or capillary rise it is possible to reduce/increase your indicated irrigation inputs to take these elements into consideration. However, in most situations these components are generally small. Additionally, the components of evaporation and transpiration (eq .2) can be combined as crop evapotranspiration, which is a measure of both soil evaporation and plant transpiration. The soil water storage in the root zone is then represented by the following equation:

$$\Delta S = P + I - ET_c \qquad \text{eq (3)}$$

Where:

ΔS	change in soil water storage [mm]
P	rainfall [mm]
I	irrigation [mm]
ET_c	crop evapotranspiration [mm]

These simplifications then leave the IrriSAT water balance deficit model as shown in Figure 2. With evapotranspiration (ET_c) removing water from the soil root zone and irrigation and rainfall adding water to the soil root zone.

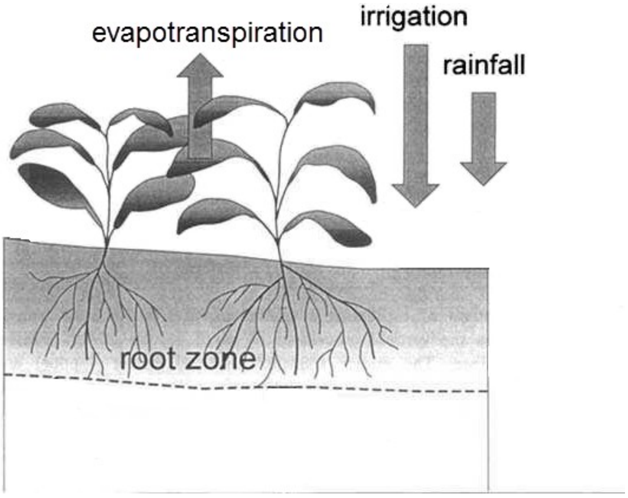

Figure 2: Conceptual IrriSAT water balance model showing inputs and outputs.

*Note: Irrigation and rainfall components above assume they are effective. i.e. not considering surface runoff.

Tracking soil water deficit through time

The soil water deficit (SWD) for any given day can then be represented by tracking the day to day water fluxes described in eq (3). This can be described as:

$$SWD_d = SWD_{d-1} + P_d + I_d - ET_{c,d} \qquad \text{eq (4)}$$

Where:

SWD_d	soil water deficit for day d [mm]
SWD_{d-1}	soil water deficit for the day prior to d [mm]
P_d	rainfall for day d [mm]
I_d	irrigation for day d [mm]
$ET_{c,d}$	crop evapotranspiration for day d [mm]

Initial conditions

To initialize the soil water balance in the root zone, an Initial Soil Water Deficit (I.S.W.D) needs to be given. In the absence of no user defined value it is assumed that heavy rainfall has taken place or an irrigation has been applied in order to fill the soil water to field capacity (*fc*) and the default value is 0 mm at the planting date on which the water balance deficit starts. This value however can be overwritten if this initial condition assumption is not met i.e. soil is below field capacity and a user defined value entered. This could be the case if the field was pre irrigated and the planting date occurred days after the irrigation or the planting was undertaken on a dry soil profile.

$$SWD_O = fc = 0, \text{(or user defined)} \qquad \text{eq (5)}$$

In the absence of an I.SW.D, the user can provide an Initial Soil Matric Potential (I.S.M.P) by installing soil matric potential sensors at the beginning of the crop. According to Brooks (1965) the Soil Matric Potential has a relationship with the volumetric water content expressed with the eq (6) below.

$$\frac{\theta - \theta_r}{\phi - \theta_r} = \begin{cases} \left({}^{h_b}/_{h}\right)^{\lambda} & , h > h_b \\ 1 & , h \le h_b \end{cases} \qquad \text{Eq (6)}$$

Where:

θ = Soil Volumetric water content $[m^3/m^3]$

θ_r = Residual soil volumetric water content $[m^3/m^3]$

ϕ = Soil porosity [-]

h_b = Air-Entry pressure [hPa] or [cm]

h = Capillary pressure or Soil Matric Potential [hPa] or [cm]

λ = Pore size distribution index [-]

The Soil porosity can be calculated according to eq (7). According to Blake (2008) the suggested value for particle density is 2.65 g/cm^3.

$$\phi = 1 - \frac{\rho_b}{\rho_s} \qquad \text{Eq (7)}$$

Where:

ρ_b = Bulk density [g/cm^3]

ρ_s = Particle density [g/cm^3]

Williams et al. (1989) developed a Pedo-transfer function using 196 samples in Australia transforming the first condition of Brooks (1965) approach to eq (8) as follows.

$$\ln \theta = A + B \times \ln h \qquad \text{Eq (8)}$$

$$A = 1{,}839 + 0{,}257 \times \ln(C_{\%}) + 0{,}381 \times 2.0 - 0{,}0001 \times (S_{\%})^2 \qquad \text{Eq (9)}$$

$$B = -0{,}303 + 0{,}093 \times \ln(\rho_b) + 0{,}0565 \times \ln(C_{\%}) - 0{,}00003 \times (S_{\%})^2 \qquad \text{Eq(10)}$$

Where:

θ = Soil Volumetric water content [m^3/m^3]

h = Capillary pressure or Soil Matric Potential [hPa] or [cm]

$C_{\%}$ = Percentage of Clay [%]

$S_{\%}$ = Percentage of Sand [%]

ρ_b = Bulk density [g/cm^3]

Further to convert the estimated volumetric water content in soil water storage eq (11) (Zhang et al., 2020) can be used.

$$SWD_0 = \theta \times \rho_b \times Sd \times 10 \qquad \text{Eq(11)}$$

Where:

SWS = Soil Water Storage [mm]

Sd = Soil depth [cm]

10 = water density [$^{mm.cm^2}/_{g}$]

Boundary constraints

Upper and lower constraints must also must be applied to the soil water storage capacity in the soil root zone in order to represent the characteristics of the real world. (i.e. a bucket can no longer be filled once it is already full, and similarly a bucket can no longer be emptied once it is empty). These upper and lower constraints are referred to as the field capacity (*fc*) and the permanent wilting point (*pwp*) respectively and are discussed further in detail in the following section.

$$pwp \leq SWD_d \leq fc \qquad \text{Whereby: } fc = 0, pwp < 0 \qquad \text{eq (12)}$$

These constraints can then be applied to the daily soil water deficit as:

$$SWD_d = \mathrm{MAX}(pwp, \mathrm{MIN}(fc, SWD_d)) \qquad \text{eq (13)}$$

The IrriSAT methodology assumes irrigation or rainfall gets applied to the soil root zone before reaching permanent wilting point, hence further simplifies eq (13) and the number of parameters needed as follows:

$$SWD_d = \mathrm{MIN}(fc, SWD_d) \qquad \text{eq (14)}$$

In order to maintain the mass balance defined in eq (1) it is assumed that if irrigation or rainfall are applied once the SWD reaches field capacity then this water is lost either through deep percolation below the root zone or through runoff. In IrriSAT this is termed ‘lost water’ - water that is not available for the crop to meet evapotranspiration requirements.

Crop Water Use (ET_c)

Crop water requirements (ET_c) can be estimated considering a climatic parameter called reference evapotranspiration (ET_o), which represents the evapotranspiration from a standardize vegetated surface, and a crop factor called crop coefficient (K_c) that relates ET_c to ET_o by the equation (Allen et al., 1998):

$$ET_c = ET_O\,K_c \qquad \text{eq (15)}$$

Where:

ET_c	crop evapotranspiration [mm]
ET_0	reference evapotranspiration [mm]
K_c	crop coefficient [-]

ETo is the rate that an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground evaporates water. The main factors affecting ETo are climatic parameters (radiation, air temperature, humidity and wind speed above all) which can be obtained from weather data. Different ETc can result between crops even under the same environmental conditions due to differences in height, canopy architecture, ground cover, and development stage. Kc incorporates the non-weather factors such as canopy architecture, crop-soil resistance and row spacings that cause ETc vary from ETo into the equation.

Determining K_c by direct methods (lysimeters, energy balance, and soil water balance) for a specific crop in a single location is expensive and not easy to do and therefore generic K_c values are typically used, which often do not match the actual crop water use. This is due to the reasons such as differences in canopy management, row spacings, and agronomic management. Indirect methods, however, can be used for this purpose to provide site specific crop coefficients. K_c has been shown to be closely related to the canopy ground cover fraction (i.e. light interception) which can be estimated from remote sensing measurements of the Normalized Difference Vegetation Index (NDVI). Thus, the IrriSAT methodology integrates information from satellite sources (NDVI; K_c) and from on-ground weather stations (ET_o) to estimate site specific crop water requirements. This approach allows site specific Kc to be determined down to each individual pixel in a satellite image and hence crop water.

Estimating reference evapotranspiration (ET_0)

Reference evapotranspiration is calculated as detailed in Allen et al. (2005) from climatic data obtained from a local weather station. This is estimated using the FAO Penman-Monteith approach as:

$$ET_O = \frac{0.408\Delta(R_n - G)y\dfrac{C_n}{T_a + 273}U_2(e_s - e_a)}{\Delta + y(1 + C_d\,U_2)} \qquad \text{eq (16)}$$

Where:

ET_0	reference evapotranspiration [mm]
R_n	net radiation at the crop surface
G	soil heat flux density [MJ m^2 day^{-1}]
T	air temperature at 2m height [˚C]
U_2	wind speed at 2 m height [m s^{-1}]
e_s	saturation vapor pressure [kPa]
e_a	actual vapor pressure [kPa]
$e_s - e_a$	saturation vapor deficit [kPa]
Δ	slope vapor pressure curve [kPa ˚C^{-1}]
Υ	psychometric constant [kPa ˚C^{-1}]
C_n	numerator constant [-]
C_d	denominator constant [-]

The FAO Penman-Monteith (FAO PM) approach is physically based, and explicitly incorporates both physiological and aerodynamic parameters. Procedures have also been developed to estimate missing climatic parameters (Allen et al. 2005; Romero et al. 2009). This approach can also be used to reference two standardized crop heights which include: short-crop (grass ~12 cm high); and tall-crop (alfalfa ~ 50 cm high) by adjusting the C_n and C_d constants.

	C_n	**C_d**
Short-Crop	900	0.34
Tall-Crop	1600	0.38

Table 1: Short-Crop and Tall-Crop FAO PM Coefficients for daily calculations

Reference crop evapotranspiration is routinely measured and reported across the world from weather station networks and is also available on a raster/grid based network for many countries.

IrriSAT uses the SILO https://www.longpaddock.qld.gov.au/silo/ climatic database available for Australia and Tall Crop ETo.

Estimating the crop coefficient (K_c)

The spectral distribution of the light reflected from plant canopies contains information that can be useful for monitoring canopy growth, transpiration, photosynthesis and for diagnosis of biotic and abiotic stresses. Leaf structure and its components such as chlorophyll or other pigments (carotenoids, anthocyanins, etc.) have an effect on the absorption of light. Leaves absorb most of the visible electromagnetic energy (less in the green region which is the reason why vegetation appears green to ours eyes) but reflects a large part of the energy in the near-infrared spectrum, which makes its spectral reflectance different from that of soil or water (Figure 3). Green vegetation shows relatively low reflectance in visible wavelength and a suddenly increase at around red-edge (700 nm) while soil tends to show a steadily increasing reflectance with increasing wavelength (Jones 2014).

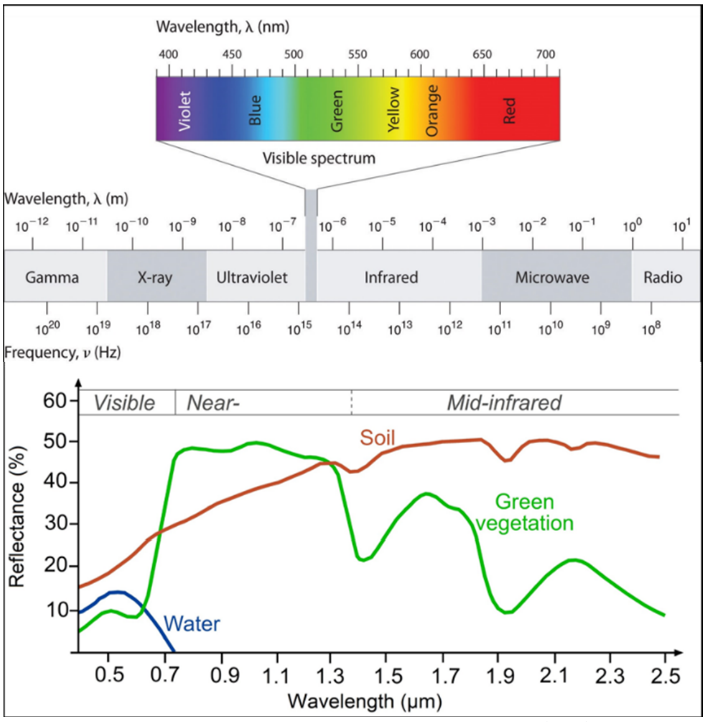

Figure 3: Wavelengths and frequency ranges of electromagnetic radiation (top) and; reflectance distribution of a green vegetation, soil and water surfaces in the visible, near-infrared and mid-infrared wavelengths.

Fully developed vegetation canopies tend to have less reflectance in the red spectrum (R) and higher reflectance in the near-infrared spectrum (NIR) as compared to developing canopies. This relationship is the base of the vegetation index known as NDVI, which is the mathematical combination of the R and NIR spectral bands as follows (Rouse et al., 1974):

$$NDVI = \frac{NIR - R}{NIR + R} \qquad \text{eq (17)}$$

There are specific sensors available that enable measuring the reflectance of an object in the spectrum range of interest. Satellites such as the Landsat 7, 8 & 9 or Sentinel 2 are equipped with these sensors and are continuously recording data from the visible and infrared spectrum range, providing information that can be used to calculate and monitor the NDVI of a target crop during a whole season. Landsat satellites provide images every 8-16 days with a spatial resolution of 30x30m. Sentinel 2 satellite images have a temporal and spatial resolutions of 5 days and 10x10m, respectively. IrriSat uses these satellites as a source of reflectance data to determine NDVI values.

As mentioned above, NDVI has been strongly correlated with crop canopy cover for various crops in semi-arid areas and can be converted to K_c values by the empirical relationships such as (Trout and Johnson 2007):

$$K_c = 1.38\ NDVI - 0.097 \qquad \text{eq (18)}$$

After determining the crop coefficient for all pixels within an image the crop coefficient for a field can be determined by calculating the arithmetic mean of all pixels within its boundary:

$$K_{c\,field} = \frac{1}{n}\sum_{i=1}^{n} K_{c,i} \qquad \text{eq (19)}$$

Where:

$K_{c,field}$	the arithmetic mean crop coefficient for a crop field [-]
$K_{c,i}$	the crop coefficient for a crop image pixel [-]
n	the number of pixels within a field

Cloud cover

IrriSAT uses its own algorithm to estimate the cloud cover. The cloud cover algorithm uses empirical thresholds to eliminate cloud pixels as well as the cloud score provided by the Sentinel-2 data set.

Irrigation Scheduling

In order to manage irrigation scheduling, an understanding of the basic soil states and regions between these states within the soil root zone need to be known (Wigginton et al). These are known as: saturation; field capacity; permanent wilting point; and readily available water, and are discussed in further detail throughout this section.

Saturation

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

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. The soil water deficit is 0 mm when the soil is at field capacity.

Permanent Wilting Point

Permanent Wilting Point occurs when the soil reaches a point where the plant can no longer extract moisture because the water content in the soil is too low for the plants roots to enable extraction. Once the soil has passed this point, water is held by the soil so tightly preventing extraction and the plant will start to die. Soil at permanent wilting point is not necessarily "dry". When the water content of a soil is below the permanent wilting point, water is still present in the soil, but plant roots are unable to access it.

Readily Available Water (RAW)

Only the water between field capacity and permanent wilting point is available to the plant. However, as the level of soil water approaches permanent wilting point, the plant has to work harder to obtain the water. To improve water-use efficiency, irrigators aim to maintain the soil water in the range that can be readily removed by the plant. This range is called the *Readily Available Water* (RAW).

Readily available water is expressed in millimetres per metre (mm/m) and indicates the depth of water (mm) held in every metre (m) of soil that can be readily removed by the plant. To achieve high production without causing waterlogging or excess drainage you need to know the RAW for each crop and field/block. Table 2 shows typical RAW values for various soil textures as well as various crop types.

Water Tension	To –20 kPa	To –40 kPa	To –60 kPa	To –100 kPa	To –1500 kPa
	A	**B**	**C**	**D**	**E**
	Water-sensitive crops such as vegetables and some tropical fruits should be irrigated.	Most fruit crops and table grapes, most tropical fruits.	Lucerne, most pasture, crops such as maize and soybeans, and grapes.	Annual pastures and hardy crops such as cotton, sorghum and winter crops.	TAW is the total water available in the soil. Plants stress well before this level is reached.
Soil texture	**Readily Available Water (RAW) mm/m**				**Total Available Water (TAW) mm/m**
Sand	35	35	35	40	60
Sandy loam	45	60	65	70	115
Loam	50	70	85	90	150
Clay loam	30	55	65	80	150
Light clay	25	45	55	70	150
Medium to heavy clay	25	45	55	65	140
Self-mulching clay	38	68	83	98	210

Table 2: Readily Available Water values for different soil textures and various crops

When to irrigate? (refill point)

After the readily available water has been used, plant roots cannot extract water as easily from the soil and growth is affected. This point is referred to as the *refill point*. As its name suggests, refill point is the time to irrigate. The drier the soil, the more water it needs to return to field capacity.

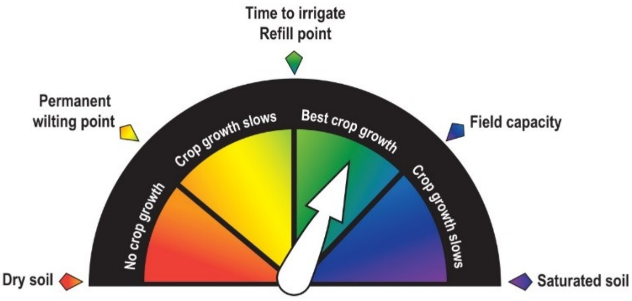

Figure 4: Soil Water 'Fuel Gauge'

Three factors should be taken into account when determining the refill point which are soil type, crop rooting depth and irrigation system. These factors may also change over time, hence the refill point may also change throughout the season.

Soil Type

Soil type considerations for setting the refill point need to take into account the water-holding capacity of the soil. Using the particle size classes (sand, silt, and clay) is possible to have reference values of refill points at specific soil depths. For example, light sandy soils the amount of water held in the soil is small per meter depth of soil so deficits should be smaller. In heavier clay soils the amount of water held in the soil is greater hence larger deficits can be used.

IrriSAT uses the SEED dataset (SEED, 2024) and the ISSS Soil texture triangle (Moeys, 2018) shown in Figure (5), to classify the soil at 10 cm depth across all NSW.

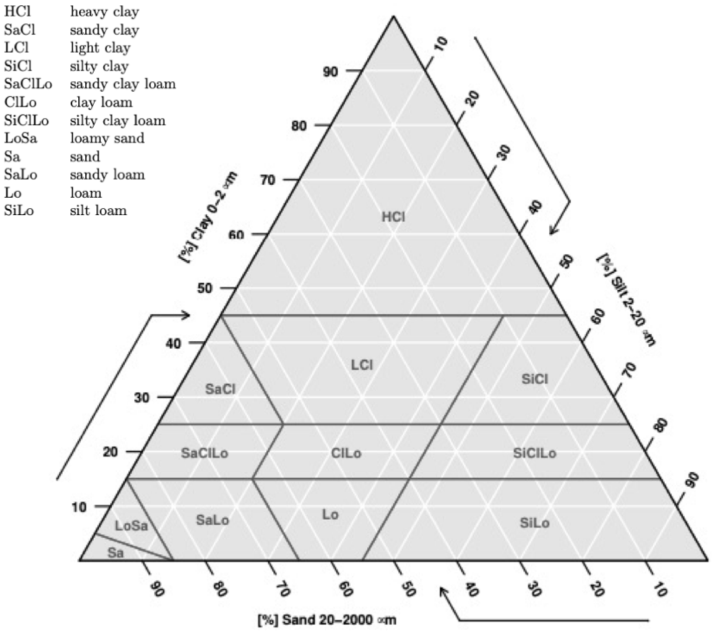

Figure 5 – ISSS Soil Texture classification Triangle (Moeys, 2018)

Rooting depth

A plant can only access water to its rooting depth and this knowledge needs to be combined with the soil type information above to set an allowable refill deficit.

Irrigation system type

Lastly the type of irrigation system being used needs to be considered when setting the refill point. On sprinkler and pressurized irrigation systems there is a limit to how much water can be applied on a daily basis, hence setting large deficits will see the irrigation system unable to cope with applying set volumes. A drip irrigation system may be limited for instance to a maximum application rate of 10 mm/day hence setting a 50 mm deficit value will see problems in high ET_c periods as the system will struggle to replenish the root zone once a 50 mm deficit has been reached on a daily basis. Hence this is why pressurized irrigations systems are generally irrigated much more frequently than surface systems. i.e. daily at peak summer ETc periods.

On surface irrigation systems application volumes are typically much higher (~ 50-100 mm) hence during high ET_c periods they still have the ability to rapidly replace large deficits, hence surface irrigation events maybe 5-10 days apart. Knowing these irrigation system limitations are important in guiding where to set the refill point to guide you with irrigation decisions.

So as a guiding principal consider these three factors above when setting the refill point. This value does not affect the water balance deficit but simply provides a point to indicate that the soil moisture profile has reached a value that is beginning to become stressful for the crop and irrigation is needed to maintain a comfortable root zone environment for plant growth.

Agronomic Performance Indicators

Water use indexes measure the agronomic performance such as productivity or profitability as opposed to the water balance. The time period considered when calculating an agronomic or economic based water use index is generally over a season or year.

Crop Water Use Index (CWUI)

The Crop Water Use Index (CWUI) or sometimes referred to as Water Use Efficiency (WUE) relates the total production returned to the amount total water consumed by the crop. It is a measure of a crop's capacity to convert water into plant biomass and can be described as:

$$Crop\ WUI_{field} = \frac{Yield}{Total\ \ Evapotranspiration} \qquad \text{eq (20)}$$

Where:

Yield	a quantitative unit representing the production generated [i.e. kg or bale]
Total Evapotranspiration	the total evapotranspiration over the growing period [ML]

Irrigation Water Use Index (IWUI)

The Irrigation Water Use Index (IWUI) relates the total production returned to only the amount of irrigation water used. It does not include rainfall and therefore is only useful for comparing nearby fields or farms within the same growing season. It should not be used to compare farms over significant distance or between seasons, where there can potentially be large differences in the amount of rainfall. The IWUI can be described as:

$$Irrigation\ WUI_{field} = \frac{Yield}{Total\ \ Irrigation\ \ Applied} \qquad \text{eq (21)}$$

Where:

Yield	a quantitative unit representing the production generated [i.e. kg or bale]
Total Irrigation	the total irrigation amount applied over the growing period [ML]

Gross Production Water Use Index (GPWUI)

The Gross Production Water Use Index (GPWUI) relates the total production returned to the amount of water used from all sources (Irrigation + Rainfall). It is generally used to compare between farms, regions and seasons and can be described as:

$$Gross\ Production\ WUI_{field} = \frac{Yield}{Total\ \ Water\ Applied} \qquad \text{eq (22)}$$

Where:

Yield	a quantitative unit representing the production generated [i.e. kg or bale]
Total Water Applied	the total irrigation and rain applied over the growing period [ML]

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