CUT 1001: AO1 – Irrigation management using canopy cover

This is an excerpt from the final report CUT 1001: **Optimising industry returns from existing soil and water research.**

To read the complete version of this final report click here

GWRDC project number: CUT 1001

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Appendix 1: Literature Reviews

Adoptable Outcome 1: Irrigation management using canopy cover

Authors: Lexie McClymont, Ian Goodwin, Mark O'Connell and Des Whitfield

1. Estimating crop evapotranspiration

Allen et al. (1998) documented what is now the standard procedure for calculating crop evapotranspiration for irrigation scheduling purposes, and in doing so provided a comprehensive explanation of factors driving and influencing crop evapotranspiration. This section provides a brief summary of the approach.

The principal factors determining evapotranspiration are evaporative demand (i.e. weather) and crop characteristics (Figure 1). Crop characteristics include resistance to transpiration, crop height, crop roughness, reflection, and understorey (Allen et al. 1998). Crop evapotranspiration under **standard conditions** (ET_c) is calculated using the following equation:

$$ET_c = (K_{cb} + K_e).ET_o \quad (1)$$

where K_{cb} is the basal crop coefficient, K_e is the soil evaporation coefficient and ET_o is reference crop evapotranspiration (Allen et al. 1998). ET_o is calculated from solar radiation, air temperature, humidity and wind speed. K_{cb} is a factor to convert ET_o to transpiration capability of a specified crop. Alternatively, a simpler version of Eqn 1 is:

$$ET_c = K_c.ET_o \quad (2)$$

where the plant transpiration and soil evaporation components of evapotranspiration are not separated and a single crop coefficient (K_c) is used (Allen et al. 1998). When the soil surface is dry, as is often the case between irrigation events in drip-irrigated vineyards, K_c is equivalent to K_{cb}.

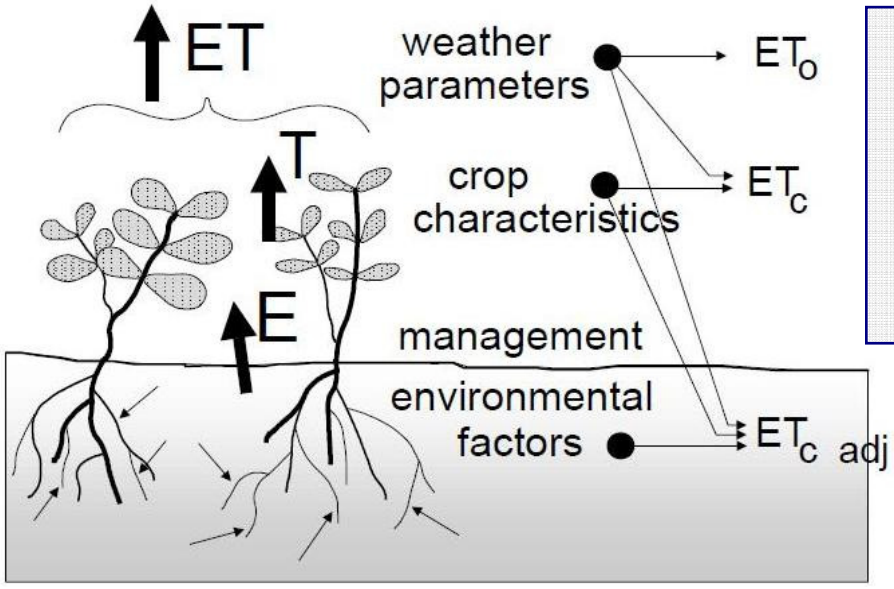


Figure 1. Factors affecting evapotranspiration with reference to related evapotranspiration concepts. From Allen et al. (1998) with permission of the Food and Agriculture Organization of the United Nations.

Crop management and environmental factors also influence evapotranspiration (Figure 1), largely via effects on canopy development and/or water availability and uptake. For example, low soil water availability or saline irrigation water will reduce transpiration while mulches will decrease soil evaporation (Allen et al. 1998). Under conditions such as these, ET_c is adjusted by altering the

K_c and/or using a water stress coefficient (K_s) or other stress coefficient (Allen et al. 1998), such that:

$$ET_{c\ adj} = (K_s.K_{cb}. + K_e).ET_o \quad (3)$$

or:

$$ET_{c\ adj} = K_s.K_c.ET_o \quad (4)$$

Allen et al. (1998) provide guidelines for adjustment of soil evaporation and crop coefficients under various climatic, environmental and crop management conditions. Generalised seasonal crop coefficient curves are shown in Figure 2 and soil and crop coefficients are discussed in more detail in sections 1.1 and 1.2.

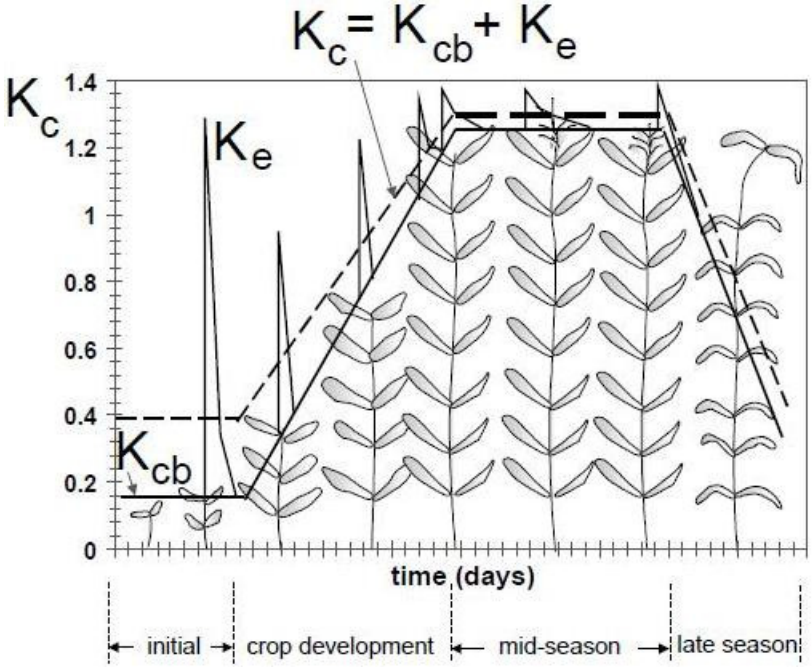


Figure 2. Generalised crop coefficient curves showing the basal crop coefficient (K_{cb}, thick line), soil evaporation (K_e, thin line) and the corresponding crop coefficient ($K_c = K_{cb} + K_e$, dashed line). The K_e 'spikes' represent increased evaporation when the soil surface has been wetted by rainfall or irrigation. From Allen et al. (1998) with permission of the Food and Agriculture Organization of the United Nations.

> "Crop evapotranspiration under standard conditions (ET_c) refers to the evaporating demand from crops that are grown in large fields under optimum soil water, excellent management and environmental conditions, and achieve full production under the given climatic conditions." Allen et al. (1998).

Water deficits are commonly utilised in winegrape production to control vegetative growth and/or improve fruit quality. Careful management of both the timing and severity of water deficits (i.e. regulated deficit irrigation, RDI) can successfully limit negative effects on yield. On the other hand, excessive water application has been linked to yield declines in grapevines, thought to be due to strong vegetative growth and shading of developing buds or competition between fruit and vegetative parts for resources (Williams et al. 1994). In such cases, even though crop transpiration is not impaired, the definition of ET_c is not strictly adhered to because "full production" is not achieved.

1.1 Soil evaporation coefficients (K_e)

In addition to evaporative demand, soil evaporation is controlled by the amount of water at the soil surface and the degree of shading by the crop canopy. Thus, irrigation system (flood, sprinkler or

drip) has a large influence on the K_e value. Soil texture, crop stage and trellis system (i.e. area of shaded soil), frequency of irrigation or rainfall and understorey (cover crop or weed) transpiration need to be taken into account when considering an appropriate K_e. Following a wetting event, soil drying is initially rapid (phase 1) and K_e is consequently high. As the soil surface dries, the evaporation process slows (phase 2) and K_e falls. The duration of phase 1 is influenced by evaporative demand with highevaporative demand resulting in a short phase 1. K_e values in drip-irrigated viticulture systems are expected to be highest early in the season when shading by the crop canopy is minimal, cover crops are active and soil moisture may be high due to early season rainfall.

Netzer et al. (2009) suggested that average seasonal K_e within a drip-irrigated vineyard was not more than 0.15, based on drainage lysimeter measurements. K_e in Netzer et al. (2009) represented soil evaporation only as no cover crop was present. Grapevines in the study were trained to an open-gable trellis system and canopy cover was estimated to reach 80 % (Netzer et al. 2009), consequently, a large proportion of the vineyard floor was shaded when the canopy fully developed. Similarly, microlysimeter measurement of soil evaporation in a drip-irrigated vineyard with canopy cover of 30 – 50 % suggested an average mid-season (January – March) K_e of 0.12 (derived from Yunusa et al. 2004). K_e was high following rainfall and irrigation events but fell to less than 0.05 during extended dry periods (derived from Yunusa et al. 2004). By contrast, average K_e in a flood-irrigated vineyard during a 100-day period between flowering and harvest, with approximately 15 rainfall or irrigation events totalling 6.5 ML/ha applied, was 0.46 (derived from Lascano et al. 1992). Likewise, Stevens (2002) found soil evaporation was high in a vineyard where micro-jets wetted the entire soil surface and canopy cover was approximately 40 % (K_e approximately 0.55). Table 1 summarises these studies.

Table 1. Soil evaporation coefficients (K_e) determined from grapevine irrigation studies.

K_e	Crop information	Source
> 0.15	Drip-irrigated; up to 80 % canopy cover; no cover crop; clay loam.	Netzer et al. (2009)
0.12	Drip-irrigated; 30 – 50 % canopy cover; no cover crop; sandy loam.	Yunusa et al. (2004)
0.55	Mini-sprinkler irrigated; 40 % canopy cover.	Stevens (2002)
0.46	Flood-irrigated; fine sandy loam.	Lascano et al. (1992)

1.2 Crop coefficients (K_c and K_{cb})

Allen et al. (1998) define generic K_c and K_{cb} values for 'typical' grapevines under standard conditions. These values integrate the effects of crop height, reflectance, leaf area, leaf age and condition, stomatal control and, in the case of K_c, evaporation from the soil in a sub-humid environment with calm to moderate wind conditions. However, these factors vary between grapevine blocks and within seasons, thus the generic crop coefficients provide a well-informed starting point for determining ET_c but require adjustment with consideration of actual growing conditions and crop characteristics to improve accuracy of estimates for irrigation scheduling.

ET_o and canopy cover have been shown to explain a large degree of the variation in grapevine transpiration between vines and throughout seasons (Yunusa et al. 1997a,b, Williams and Ayars 2005, McClymont et al. 2009, Netzer et al. 2009, Edwards and Clingeleffer 2011). Since canopy cover is easily measured and a major driver of grapevine transpiration, adjustment of crop coefficients for canopy cover provides a good opportunity for improving ET_c calculations. The

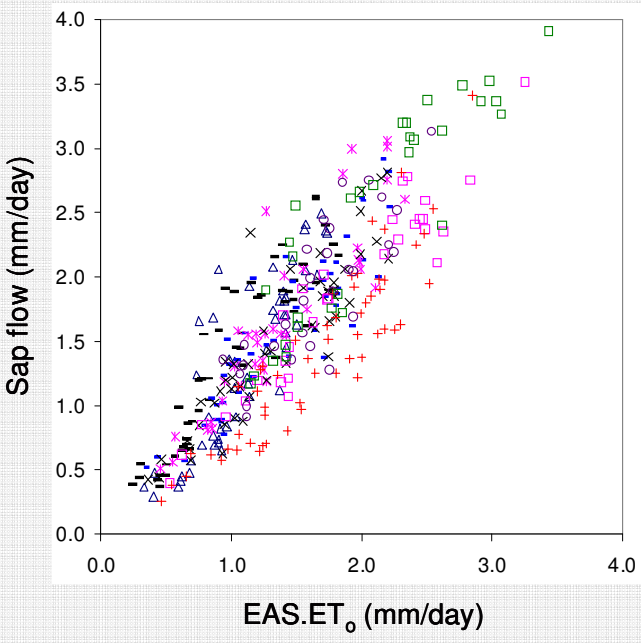
generic values of K_c and K_{cb} provided by Allen et al. (1998) vary at different stages of the season (initial-, mid- and late-season) and this accounts for seasonal changes in canopy cover and, hence, changes in ET_c. However, at the same growth stage, canopy cover can vary substantially depending on vine age, trellis system and growing conditions. The methods described in Allen et al. (1998) for adjusting K_c or K_{cb} when canopy cover is less than 'typical' are complex and are not crop specific. Simple, practical methods of adjusting crop coefficients for differences in grapevine canopy cover will improve the accuracy of calculations of irrigation requirements.

ET_o and canopy cover are the major drivers of grapevine transpiration

The importance of evaporative demand (ET_o) and canopy cover in determining grapevine water use is highlighted by data collected in Central Victoria during the 2006/07 and 2007/08 seasons ('Managing soil and water to target quality and reduce environmental impact', GWRDC project DPI 04/04).

Transpiration in well-watered Shiraz grapevines increased linearly with increasing evaporative demand and canopy cover (Figure 3, McClymont et al. 2009). Transpiration was measured by sap flow. Canopy cover was expressed as effective area of shade (EAS) to account for changes in fractional radiation interception throughout a day. Goodwin (2009) describes how to conduct shade measurements and EAS is calculated as:

$$\text{EAS} = \frac{\text{Shade (am)} + \text{Shade (midday)} + \text{Shade (pm)}}{3}$$



2. Adjusting crop evapotranspiration for canopy cover

Williams and Ayars (2005) determined that grapevine (*Vitis vinifera* L. cv. Thompson Seedless grown in California) water use and K_c are linearly related to a number of measures of canopy cover, including the amount of shade cast on the ground at midday, vine leaf area and leaf area index. Of the three canopy cover measures, Williams and Ayars (2005) concluded that amount of shade was the most important determinant of grapevine water use and K_c could be calculated as:

$$K_c = 1.7 f\text{CC} - 0.008 \quad (5)$$

where *f*CC is canopy cover measured as fractional radiation interception at midday (Williams and Ayars 2005). Vines in this study were grown in a weighing lysimeter and kept in a constantly well-watered state by irrigating whenever weight change indicated vine evapotranspiration equivalent to 2 mm. Later studies by Williams et al. (2009a,b) indicate that irrigating grapevines surrounding the lysimeter to match potential transpiration (i.e. lysimeter water use) led to reduced yields compared to vines irrigated with a fraction (60 – 80 %) of lysimeter water use despite vegetative growth continuing to increase with greater water supply. Eqn 5, then, may not strictly comply with the definition of ET_c that requires plants "achieve full production".

A similar study by Selles et al. (2011) using the eddy-covariance method to determine ET_c of Thompson Seedless grapevines grown on parronal español trellis in the Acongagua Valley, Chile, concluded that:

$$K_c = 1.34.fCC - 0.1585 \quad (6)$$

again, *f*CC is fractional radiation interception at midday. The lower slope of this relationship, compared to Eqn 5, may reflect the fact that the study was conducted in a commercial vineyard. Irrigation could have been less than required to constitute 'well-watered' conditions throughout the season, resulting in crop transpiration lower than potential transpiration and lower soil evaporation due to less frequent irrigation events. However, the crop would have been managed with the aim of achieving 'full production' and thus, calculation of evapotranspiration based on Eqn 6 would be considered consistent with the definition of ET_c.

In both studies (Williams and Ayars 2005 and Selles et al. 2011) the grapevines were drip-irrigated and canopy cover reached 75 % or greater, therefore K_e is expected to be low and K_c approximately equal to K_{cb} for most of the study periods. The apparent negative values of K_c when canopy cover is zero could be due to inclusion of non-transpiring material (wood or trellis system) in measurements of canopy cover. Additionally, if the proportion of shaded leaf area increases with increasing canopy cover the contribution of these leaves to whole vine transpiration could increase the slope of the relationship and force a negative intercept. Neither Williams and Ayars (2005) or Selles et al. (2011) indicate whether or not the intercept values in their equations are significant.

Field measurements of canopy cover are simple and can be conducted by growers with inexpensive equipment. Goodwin (2009, Figure 4a) and Battany (2010, Figure 4b) describe two methods and associated calculations to determine fractional or percent canopy cover. E&J Gallo Winery in California have relied on canopy cover measurements to determine irrigation recommendations for the company's vineyards and contracted growers for several years (pers. comm. Martine Mendez-Costabel).



Figure 4. Measurement of canopy cover can be simply performed using the a) stick (from Goodwin 2009) or b) 'Paso panel' methods (from Battany (2010), Copyright (c) [2010] Regents of the University of California).

3. Irrigation management tools

An irrigation spreadsheet (available from Ian Goodwin, email: ian.goodwin@dpi.vic.gov.au, or telephone: (03) 5833 5240) and powerpoint presentation were developed to increase grower understanding and adoption of irrigation scheduling based on calculation of ET_p adjusted for canopy cover. The spreadsheet enables growers to:

- create seasonal irrigation budgets based on historical ET_o data and canopy cover,
- plan their irrigation schedules for appropriate irrigation depths and frequencies, and
- monitor and predict irrigation requirements, based on current and forecast ET_o and canopy cover data, and compare these with irrigation supply.

The spreadsheet has been designed to cope with a range of soil and climate conditions so that growers throughout Australia can use it.

3.1 Seasonal irrigation budget

The **seasonal irrigation budget** enables forward planning and investigation of different weather scenarios and irrigation strategies.
Irrigation budgets require the following data;

- Historical evaporative demand (ET_o) and rainfall
- Typical canopy cover
- Rootzone extent
- Soil water holding capacity
- Estimation of the soil evaporation coefficient (K_e)

Water budgeting is a useful tool to estimate the seasonal irrigation requirements of a vineyard. The spreadsheet allows growers to forward plan and run different scenarios for risk analysis. For example, what is the irrigation requirement if there is no winter and spring rainfall? What is the irrigation requirement for grapevines grown under RDI?
In the spreadsheet water budget, monthly vineyard water use capability (i.e. ET_c) is calculated from long-term average ET_o, canopy cover and K_{cb} and K_e. Historical ET_o can be obtained from a number of sources (Appendix A). Assessment of average block canopy cover is described by Goodwin (2009) and Battany (2010). K_{cb} is estimated to be equal to 1.3.*f*CC, based on Selles et al. (2011, Eqn 6), alternatively, growers may wish to base K_{cb} on Williams and Ayars (2005, Eqn 5). K_e is influenced by irrigation type (e.g. drip, sprinkler or flood), inter-row conditions (e.g. bare soil, active cover crop or mulch) and soil shading by the canopy (Allen et al. 1998), as discussed in section 1.1, and is set by the grower based on site conditions. A mid-season K_e of 0.1 is reasonable for drip-irrigated vineyards. Stored soil moisture in the root-zone from winter and within season rainfall is deducted from ET_c and a stress coefficient is applied to give the irrigation requirement of the vineyard.

Figure 5 shows an example water budget for a vineyard in the Goulburn Valley. Irrigation requirement was estimated for a vineyard with 40 % mid-season canopy cover (*f*CC = 0.4). The example vineyard had a root-zone depth of 500 mm, a clay loam soil, adequate winter rainfall to wet up the entire root-zone and average within season rainfall. Effective rainfall was set to 75 %. In other words, 75 % of rain during the season would be captured in the root-zone. The vineyard was drip-irrigated and water use from the understorey (i.e. soil evaporation and cover crop water use) was set to 60 % of ET_o in September (K_e = 0.6). Typically in September, canopy cover is low, creating little shading of the inter-row, and rainfall events are light and frequent so that free water is often available for evaporation and transpiration by the active inter-row sward. Gradual drying of the soil surface was recognised by lowering K_e to 0.3 in October. For the remainder of the season, K_e was decreased to 0.1 as the canopy develops creating more shade, the inter-row sward becomes

non-active and the area of soil surface wetted is limited. K_{cb} was based on Selles et al. (2011, i.e. $K_{cb} = 1.3.fCC$). The example shows that irrigation would commence in November and increase to a maximum in January of approximately 20 mm per week (0.2 ML/ha). Total seasonal irrigation requirement was predicted to be 350 mm (3.5 ML/ha).

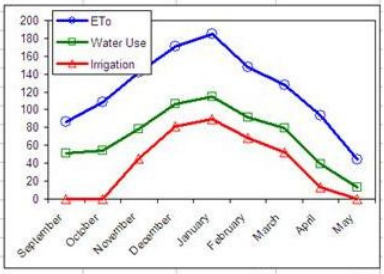
Vineyard Water Budget

Month	Long-term Average ETo (mm)	Canopy cover (%)	Crop Coefficient (K_{cb})	Soil Evaporation Coefficient (K_e)	Vineyard Water Use (mm)	Average Rainfall (mm)	Soil Reserve (mm)	Stress Coefficient	Irrigation Requirement (mm)
September	86	0	0.0	0.6	52	44	21	1.0	0
October	109	15	0.2	0.3	54	49	4	1.0	0
November	142	35	0.5	0.1	79	39	0	1.0	45
December	171	40	0.5	0.1	106	33	0	1.0	81
January	185	40	0.5	0.1	115	34	0	1.0	89
February	148	40	0.5	0.1	92	31	0	1.0	69
March	127	40	0.5	0.1	79	35	0	1.0	53
April	93	25	0.3	0.1	40	35	0	1.0	13
May	44	15	0.2	0.1	13	48	23	1.0	0
TOTAL (mm)					628				350
TOTAL (ML/ha)					6.3				3.5

Effective Rainfall (%) 75

Soil Water Reserve in Root-zone

Layer	Root-zone extent Depth (mm)	Root-zone extent Lateral (%)	Soil Texture	RAW or DAW (%)	Soil Reserve (mm)
1	300	100	clay loam	8	24
2	200	100	clay loam	8	16
3					
TOTAL	500				40



Irrigation Budget | Irrigation Scheduling Plan | Irrigation Records

Figure 5. An example water budget for a vineyard in the Goulburn Valley. Unshaded cells indicate that the grower enters the data while shaded cells indicate that values are calculated automatically.

Calculations in shaded cells of the spreadsheet are performed automatically while the grower can alter information in the remaining cells to 'test' different scenarios (Figure 5). For example, growers can change the 'canopy cover' data to match their individual blocks; the 'soil evaporation coefficient' can be changed depending on the irrigation system and cover crop and the 'stress coefficient' can be modified if deficit irrigation strategies are employed; monthly reference crop evapotranspiration (ET_o), rainfall (and the percent effective rainfall) and soil water holding capacity data can be changed to suit other regions or low rainfall scenarios. Extension material from GWRDC and other sources provide growers with information regarding critical periods for water supply and management of deficit irrigation (Goodwin 1995, Goodwin 2002, Kriedemann and Goodwin 2003, CRCV 2005, Chalmers 2009), these resources should be consulted when examining scenarios for drought or deficit irrigation.

3.2 Planning an irrigation schedule

The **irrigation scheduling plan** determines the time taken for vines to deplete available soil water and helps avoid over-irrigation or excessive water stress.
Calculation of available soil water requires the following data:

- Depth of the root system
- Size of the wetted pattern
- Soil water holding capacity

Calculation of ideal irrigation run-times and intervals are then based on irrigation system details and predicted crop water use (from the irrigation budget).

An irrigation scheduling plan is the first step to implementing good irrigation management. The aim of a plan is to calculate irrigation frequency for each month of the season from the ideal amount of irrigation to apply in a single event and vineyard water use. In other words, the plan calculates the number of days taken for the vines to deplete the previous irrigation based on average climatic conditions. Data on the ideal amount of irrigation, long-term average ET_o, canopy cover, K_e, a stress coefficient and vineyard details of vine and row spacing are needed for the calculation.

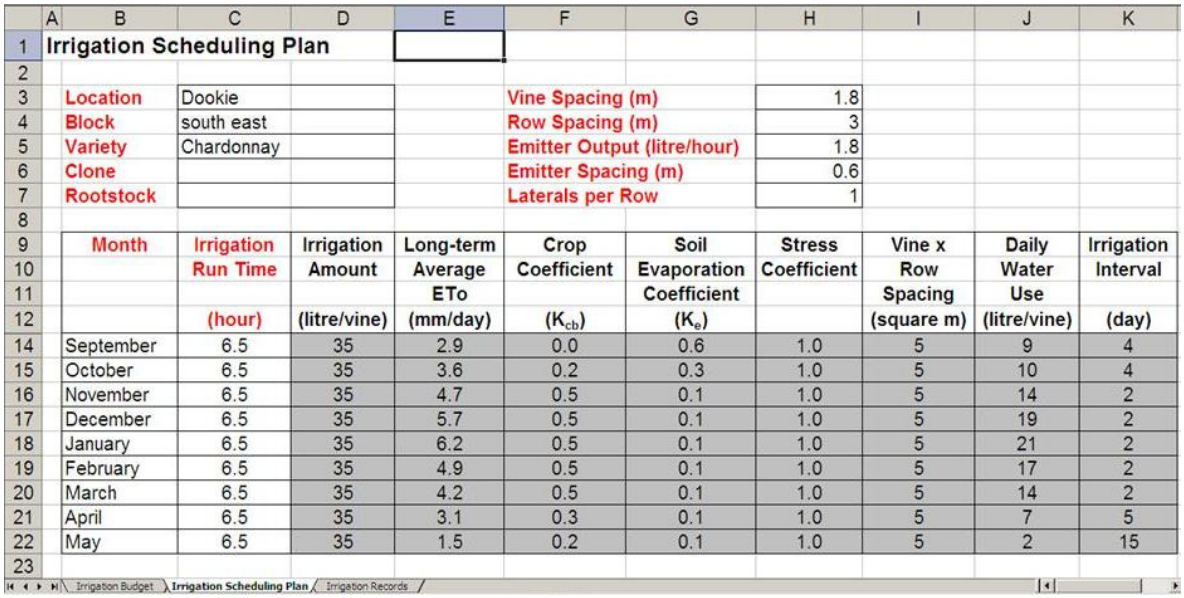
The ideal irrigation amount is based on the size of the wetting pattern, the depth of the main fibrous root-zone and the water holding capacity of the soil. Knowing the ideal irrigation amount helps to avoid losing water to deep drainage by setting run-times that are too long. A useful software tool to estimate drip irrigation run-time (and hence the ideal amount of irrigation to apply) is Wetup (http://www.clw.csiro.au/products/wetup/). Although designed for the sugarcane industry it does provide an indication of the wetting pattern under drip irrigation for different soil types. Alternatively, irrigation runtime (I, h) can be calculated assuming a cylinder shaped wetting pattern from:

$$I = \frac{3.14 \times R^2 \times D \times 1000}{Q} \times RAW \qquad (7)$$

where R (m) is the radius of the wetting pattern, D (m) is the depth of the fibrous root-zone, Q is the emitter discharge rate (L/h) and RAW (m^3/m^3) is the readily available water. RAW values of 0.08 and 0.06 m^3/m^3 can be used for heavy and light soils, respectively.

In the spreadsheet, daily water use is calculated from long-term average ET_o, canopy cover, K_e and the stress coefficient (this data is picked up from the water budget, Figure 5). The volume of water applied in a single irrigation event is calculated based on vine, row and emitter spacing data and the ideal run-time (this information is entered by the grower). Irrigation interval is simply the amount of irrigation applied divided by the daily water use. Unlike the calculation of irrigation requirement for water budgeting, this calculation does not take into account possible rainfall events. The irrigation frequency is therefore appropriate for dry periods with ET_o similar to the historical average; adjustments to actual irrigation interval should be made following significant rainfall events or during periods of high ET_o.

Figure 6 shows an example scheduling plan for the vineyard used in the previous water budget example (Figure 5). The vineyard was irrigated by 1.8 L/h drippers with a wetted radius of approximately 0.3 m. Estimated irrigation run time was 6.5 h to wet to 0.5 m depth. The example shows that the predicted irrigation interval is 2 days from November to March.



Irrigation Scheduling Plan

Location	Dookie	Vine Spacing (m)	1.8	
Block	south east	Row Spacing (m)	3	
Variety	Chardonnay	Emitter Output (litre/hour)	1.8	
Clone		Emitter Spacing (m)	0.6	
Rootstock		Laterals per Row	1	

Month	Irrigation Run Time (hour)	Irrigation Amount (litre/vine)	Long-term Average ETo (mm/day)	Crop Coefficient (K_{cb})	Soil Evaporation Coefficient (K_e)	Stress Coefficient	Vine x Row Spacing (square m)	Daily Water Use (litre/vine)	Irrigation Interval (day)
September	6.5	35	2.9	0.0	0.6	1.0	5	9	4
October	6.5	35	3.6	0.2	0.3	1.0	5	10	4
November	6.5	35	4.7	0.5	0.1	1.0	5	14	2
December	6.5	35	5.7	0.5	0.1	1.0	5	19	2
January	6.5	35	6.2	0.5	0.1	1.0	5	21	2
February	6.5	35	4.9	0.5	0.1	1.0	5	17	2
March	6.5	35	4.2	0.5	0.1	1.0	5	14	2
April	6.5	35	3.1	0.3	0.1	1.0	5	7	5
May	6.5	35	1.5	0.2	0.1	1.0	5	2	15

Irrigation Budget | Irrigation Scheduling Plan | Irrigation Records

Figure 6. An example irrigation scheduling plan for a vineyard in the Goulburn Valley. Irrigation run time was determined from the wetting pattern size, the depth of the main fibrous root-zone and the water holding capacity of the soil (Eqn 7). Daily water use was calculated using data from Figure 5 including K_{cb}, K_e, the stress coefficient and historical ET_o data. Irrigation interval was calculated by dividing irrigation amount by the daily water use. Values in shaded cells are either calculated automatically or picked up from the 'Irrigation Budget' worksheet (Figure 5). Values in unshaded cells are entered by the grower.

Particular site considerations and grower objectives regarding yield and fruit quality targets will influence irrigation scheduling plans and real-time irrigation management. For example, salt accumulation requires leaching fractions to be applied in certain vineyards and the timing of deficit irrigation can influence yield and fruit quality impacts. Growers are advised to consult Goodwin (1995), Goodwin and Kriedemann (2003), Giddings (2004) and Biswas et al. (2009) for more information.

3.3 Real-time irrigation scheduling

The **irrigation recording sheet** predicts real-time crop water use and monitors irrigation. The following data is needed:

- Actual and forecast evaporative demand (ET_o) and rainfall
- Canopy cover
- Applied irrigation

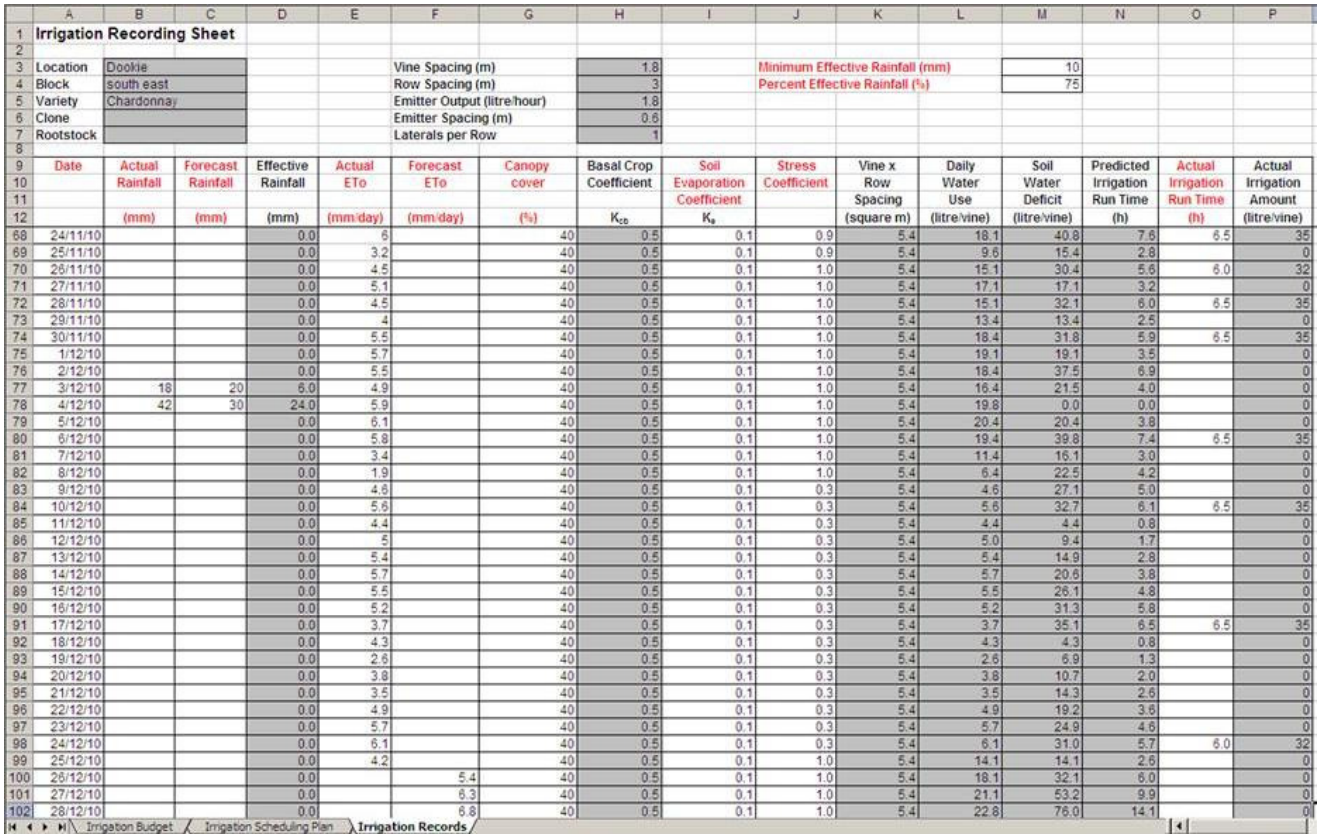
The final step in good irrigation management is to use real-time and forecast climate data combined with estimates of canopy cover to schedule and monitor irrigation. Growers commonly base day-to-day irrigation decisions on the previous day(s) and predictions of temperature and rainfall. Such decisions can be improved by using actual and forecast ET_o (Appendix A) and measurements of canopy cover (Goodwin 2009, Battany 2010). The aim is to apply the ideal irrigation amount (section 3.2 and Eqn 7) when the RAW in the root-zone has been depleted. The spreadsheet aids these calculations and provides records of applied irrigations.

Within the spreadsheet, actual and forecast rainfall and ET_o data, canopy cover data, K_e and stress coefficients are entered by the user. Effective rainfall thresholds are set by the grower and may be adjusted for site factors (such as soil type, root system architecture, canopy interception of rainfall

and slope) that effect soil water content and plant access to soil water. Growers often over-estimate the effectiveness of rainfall events (Giddings 2004). Consequently, soil moisture monitoring should be used to judge the effectiveness of rainfall events in wetting the soil profile and to inform decisions regarding delaying and re-starting irrigation following rainfall events. Predicted irrigation run-time is calculated from the cumulative ET_c since the previous irrigation and growers enter actual irrigation run-times.

Figure 7 shows an example irrigation recording sheet for the vineyard used in the previous examples (Figure 5 and 6). Effective rainfall was calculated automatically assuming 75 % of rainfall above 10 mm contributes water to the vine root-zone. K_{cb} was calculated based on Selles et al. (2011; i.e. $K_{cb} = 1.3*fCC$). Irrigation was applied when the predicted run-time approached the ideal amount of irrigation to apply (6.5 h in this example). Irrigation was scheduled approximately every two days in late-November. Irrigation was then delayed due to a forecast rainfall event in early-December. A post-fruit set RDI period was imposed mid-December to control vegetative growth (K_s=0.3) and the irrigation interval temporarily increased. The grower entered forecast ET_o values for 26 to 28 December and planned the next irrigation event for 27 December.

Efficient irrigation management requires that irrigation schedules be adjusted depending on actual or predicted conditions. Note that irrigations in the example are delayed following rainfall events and irrigation volumes are decreased when large rainfall events are predicted or evaporative demand is lower than the historical average (Figure 7). Similarly, irrigation frequency would need to be increased if evaporative demand were high. To minimise risks associated with heatwaves, Giddings (2004) recommends that growers monitor weather forecasts and adjust farm schedules to ensure that adequate water (including subsoil moisture) is available to grapevines *prior* to extended periods of hot weather. Ideally, scheduling of irrigation based on weather conditions and canopy cover should be used in conjunction with soil moisture monitoring to determine when to initiate irrigation at the start of a season and when to re-start irrigation following rainfall events. Irrigation is often initiated before soil moisture has been drawn down at the start of the season. Furthermore, the effectiveness of large rainfall events can easily be misjudged. Charlesworth (2005) provides a comprehensive summary of commercial soil moisture sensors and case studies illustrating the use of these sensors to fine-tune irrigation scheduling.



Irrigation Recording Sheet																
Location	Dookie				Vine Spacing (m)		1.8		Minimum Effective Rainfall (mm)			10				
Block	south east				Row Spacing (m)		3		Percent Effective Rainfall (%)			75				
Variety	Chardonnay				Emitter Output (litre/hour)		1.8									
Clone					Emitter Spacing (m)		0.6									
Rootstock					Laterals per Row		1									
Date	Actual Rainfall (mm)	Forecast Rainfall (mm)	Effective Rainfall (mm)	Actual ETo (mm/day)	Forecast ETo (mm/day)	Canopy cover (%)	Basal Crop Coefficient K_{cb}	Soil Evaporation Coefficient K_e	Stress Coefficient	Vine x Row Spacing (square m)	Daily Water Use (litre/vine)	Soil Water Deficit (litre/vine)	Predicted Irrigation Run Time (h)	Actual Irrigation Run Time (h)	Actual Irrigation Amount (litre/vine)
24/11/10			0.0	6		40	0.5	0.1	0.9	5.4	18.1	40.8	7.6	6.5	35
25/11/10			0.0	3.2		40	0.5	0.1	0.9	5.4	9.6	15.4	2.8		0
26/11/10			0.0	4.5		40	0.5	0.1	1.0	5.4	15.1	30.4	5.6	6.0	32
27/11/10			0.0	5.1		40	0.5	0.1	1.0	5.4	17.1	17.1	3.2		0
28/11/10			0.0	4.5		40	0.5	0.1	1.0	5.4	15.1	32.1	6.0	6.5	35
29/11/10			0.0	4		40	0.5	0.1	1.0	5.4	13.4	13.4	2.5		0
30/11/10			0.0	5.5		40	0.5	0.1	1.0	5.4	18.4	31.8	5.9	6.5	35
1/12/10			0.0	5.7		40	0.5	0.1	1.0	5.4	19.1	19.1	3.5		0
2/12/10			0.0	5.5		40	0.5	0.1	1.0	5.4	18.4	37.5	6.9		0
3/12/10	18	20	6.0	4.9		40	0.5	0.1	1.0	5.4	16.4	21.5	4.0		0
4/12/10	42	30	24.0	5.9		40	0.5	0.1	1.0	5.4	19.8	0.0	0.0		0
5/12/10			0.0	6.1		40	0.5	0.1	1.0	5.4	20.4	20.4	3.8		0
6/12/10			0.0	5.8		40	0.5	0.1	1.0	5.4	19.4	39.8	7.4	6.5	35
7/12/10			0.0	3.4		40	0.5	0.1	1.0	5.4	11.4	16.1	3.0		0
8/12/10			0.0	1.9		40	0.5	0.1	1.0	5.4	6.4	22.5	4.2		0
9/12/10			0.0	4.6		40	0.5	0.1	0.3	5.4	4.6	27.1	5.0		0
10/12/10			0.0	5.6		40	0.5	0.1	0.3	5.4	5.6	32.7	6.1	6.5	35
11/12/10			0.0	4.4		40	0.5	0.1	0.3	5.4	4.4	4.4	0.8		0
12/12/10			0.0	5		40	0.5	0.1	0.3	5.4	5.0	9.4	1.7		0
13/12/10			0.0	5.4		40	0.5	0.1	0.3	5.4	5.4	14.9	2.8		0
14/12/10			0.0	5.7		40	0.5	0.1	0.3	5.4	5.7	20.6	3.8		0
15/12/10			0.0	5.5		40	0.5	0.1	0.3	5.4	5.5	26.1	4.8		0
16/12/10			0.0	5.2		40	0.5	0.1	0.3	5.4	5.2	31.3	5.8		0
17/12/10			0.0	3.7		40	0.5	0.1	0.3	5.4	3.7	35.1	6.5	6.5	35
18/12/10			0.0	4.3		40	0.5	0.1	0.3	5.4	4.3	4.3	0.8		0
19/12/10			0.0	2.6		40	0.5	0.1	0.3	5.4	2.6	6.9	1.3		0
20/12/10			0.0	3.8		40	0.5	0.1	0.3	5.4	3.8	10.7	2.0		0
21/12/10			0.0	3.5		40	0.5	0.1	0.3	5.4	3.5	14.3	2.6		0
22/12/10			0.0	4.9		40	0.5	0.1	0.3	5.4	4.9	19.2	3.6		0
23/12/10			0.0	5.7		40	0.5	0.1	0.3	5.4	5.7	24.9	4.6		0
24/12/10			0.0	6.1		40	0.5	0.1	0.3	5.4	6.1	31.0	5.7	6.0	32
25/12/10			0.0	4.2		40	0.5	0.1	1.0	5.4	14.1	14.1	2.6		0
26/12/10			0.0		5.4	40	0.5	0.1	1.0	5.4	18.1	32.1	6.0		0
27/12/10			0.0		6.3	40	0.5	0.1	1.0	5.4	21.1	53.2	9.9		0
28/12/10			0.0		6.8	40	0.5	0.1	1.0	5.4	22.8	76.0	14.1		0

Irrigation Budget | Irrigation Scheduling Plan | Irrigation Records

Figure 7. An example irrigation recording sheet showing when and how much irrigation was applied to a vineyard in the Goulburn Valley. Actual run-time aimed to match the ideal amount of irrigation to apply (6.5 h in this example) but was altered with consideration of actual and forecast conditions. Unshaded cells indicate that the grower enters the data while shaded cells indicate that values are calculated automatically.

4. Advances in remote-sensing and irrigation scheduling tools

Campos et al. (2010) investigated the use of remotely-sensed vegetation indices, rather than ground-based measures of canopy cover, to predict ET_c of grapevines and found strong relationships between K_{cb} and the normalised difference vegetation index (NDVI) and the soil adjusted vegetation index (SAVI) derived from satellite images. More recently, Whitfield et al. (2011) determined average regional K_c, K_{cb} and K_e values for grapevines, grown in the Sunraysia region of Australia, based on satellite-derived NDVI and crop evapotranspiration. O'Connell and Mendez-Costabel (2011) described the use of such satellite data for irrigation scheduling in California. These studies confirm the validity of predicting ET_c of grapevines based on remotely-sensed vegetation indices (reviewed by Glenn et al. 2007 and Allen et al. 2011). This approach is used by CSIRO for the Irrisat-SMS irrigation scheduling service (www.irrigateway.net/tools/sms/, Hornbuckle et al. 2008) currently being trialled by the grape industry in Australia (contact John Hornbuckle for further information: www.irrigateway.net/Contact.aspx). Remote-sensing of NDVI enables block-specific irrigation scheduling advice to be provided to a large number of growers on a regular basis (Calera-Belmonte et al. 2005, Hornbuckle et al. 2008). Remote-sensing of actual evapotranspiration (SEBAL or METRIC methods) or water status (by thermography) can provide further information to aid irrigation scheduling, for example, allowing growers to prioritise irrigation scheduling of different blocks or determine when to initiate irrigation at the start of a season or re-start irrigation following rainfall events. Irrigation advice services based on remote sensing of evapotranspiration or canopy temperature are being developed and trialled overseas.

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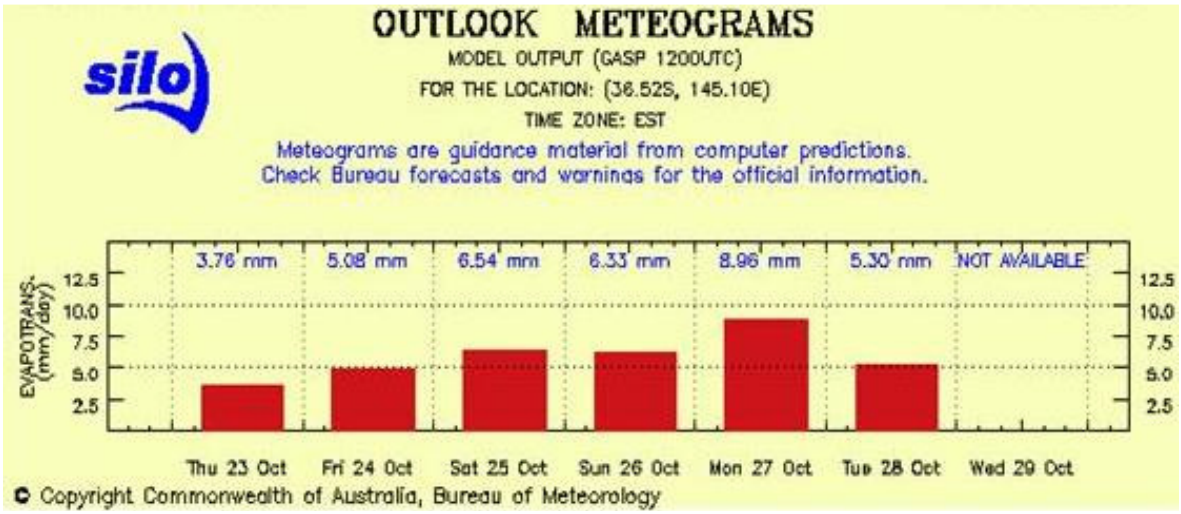
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Appendix A. Measurement of reference crop evapotranspiration

Long-term average, previous days and forecast reference crop evapotranspiration (ET_o) data are all useful for irrigation management. Long-term average data is used to build an annual water budget so that total monthly irrigation requirements can be estimated for purchasing or allocating water. Long-term ET_o can be used to plan an approximate irrigation frequency based on average climatic conditions. Previous days ET_o is needed to calculate the actual irrigation requirement to replenish the soil with moisture depleted from ET_c. Forecast ET_o is used to predict when the next irrigation is due. Calculation of ET_o is described by Allen et al. (1998).

Historical and recent reference crop evapotranspiration (ET_o) can be obtained from the Bureau of Meteorology (BOM; http://www.bom.gov.au/watl/eto/). Seven day forecast ET_o can be obtained from BOM in meteogram form (http://reg.bom.gov.au/products/reg/access/). An example meteogram is shown in Figure A-1. Note that users must be registered to obtain forecast ET_o data from the BOM. CSIRO provides recent and forecast ET_o for selected locations on the irriGATEWAY website (http://weather.irrigateway.net/). A number of other agencies provide current ET_o data for specific locations.



Irrigators should be aware that data from agencies other than the BOM may not be quality assured. Furthermore, ET_o is influenced by site conditions – ET_o calculated from weather measurements at an airport will differ from ET_o calculated from measurements within a nearby orchard. An irrigator using a consistent source of ET_o data will be able to adjust ET_c calculations for influences of weather station site. However, they will need some understanding of ET_o calculations to be able to recognise possibly erroneous data from sources that do not have a quality assurance process.

Appendix 2: Powerpoint presentations
In the actual presentations, notes are provided as a guide for the presenter

Adoptable Outcome 1: Irrigation management using canopy cover

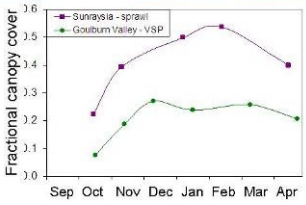
Authors: Lexie McClymont, Ian Goodwin, Mark O'Connell and Des Whitfield

Irrigation Management Using Canopy Cover

Presenter(s)

Introduction



Introduction

1. Calculating irrigation requirement
2. Spreadsheet tool for
   a) irrigation budget
   b) irrigation plan
   c) real-time scheduling
3. Future irrigation tools and services

1. Irrigation requirement

- Crop evapotranspiration – based on canopy cover
- Maximum allowable depletion – soil water availability

Crop evapotranspiration

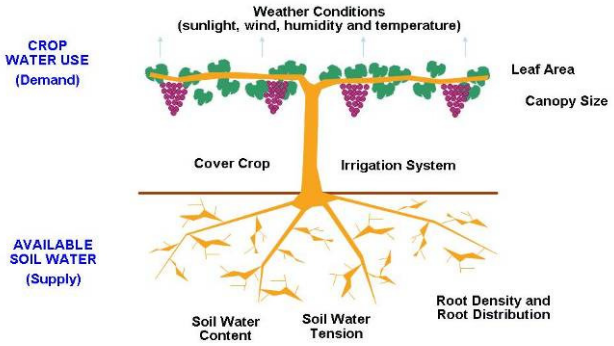
Guidelines for computing crop water requirements

by Allen et al. 1998

FAO Irrigation and drainage paper 56

www.fao.org

Crop evapotranspiration



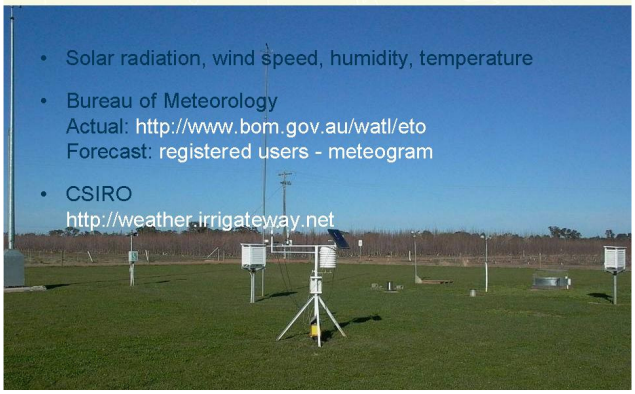
Crop evapotranspiration - ET_c

$$ET_c = (K_{cb} + K_e).ET_o$$

where:

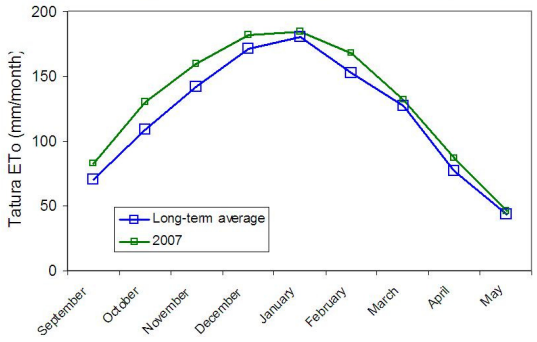
- ET_o is reference crop evapotranspiration (water use of irrigated grass)
- K_{cb} is the crop coefficient (convert ET_o to grapevine transpiration)
- K_e is the soil evaporation coefficient (convert ET_o to soil evaporation)

Reference crop evapotranspiration - ET_o



- Solar radiation, wind speed, humidity, temperature
- Bureau of Meteorology
  Actual: http://www.bom.gov.au/watl/eto
  Forecast: registered users - meteogram
- CSIRO
  http://weather.irrigateway.net

Reference crop evapotranspiration - ET_o



Data source: Bureau of Meteorology

Soil evaporation coefficient - K_e

- Wetted area, understorey components, soil texture and water content, shade



Soil evaporation coefficient - K_e

K_e for vineyards:

Ke	Crop information	Source
> 0.15	Drip-irrigated; up to 80 % canopy cover; no cover crop; clay loam.	Netzer et al. (2009)
0.12	Drip-irrigated; 30 – 50 % canopy cover; no cover crop; sandy loam.	Yunusa et al. (2004)
0.55	Mini-sprinkler irrigated; 40 % canopy cover.	Stevens (2002)
0.46	Flood-irrigated; fine sandy loam.	Lascano et al. (1992)

Useful estimate:

Fraction of the vineyard understorey that is well-watered and sunlit.

Basal crop coefficient - K_{cb}

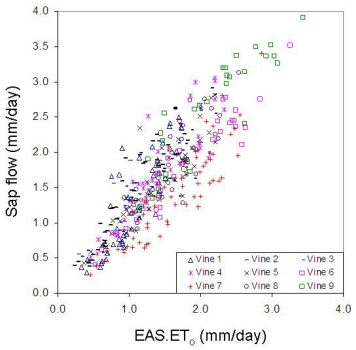
- Crop characteristics
  - crop height, leaf area, leaf age and condition

Crop	$K_{cb\ early}$	$K_{cb\ mid}$	$K_{cb\ late}$
Wine grapes	0.15	0.80	0.40

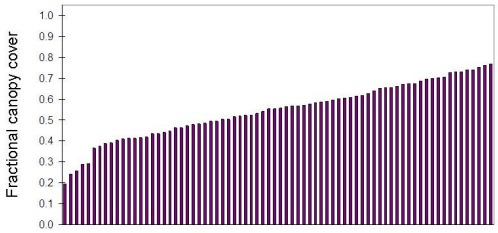
From Table 17 in Allen et al. (1998)

Basal crop coefficient - K_{cb}

- Crop characteristics - canopy cover is a major driver of grapevine transpiration



Basal crop coefficient - K_{cb}

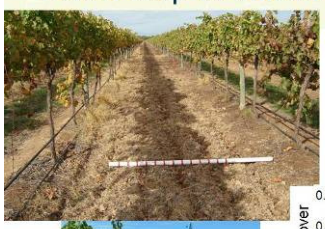


Basal crop coefficient - K_{cb}

- Williams and Ayars (2005)
  K_c = 1.7 x fractional Canopy Cover (%) - 0.008
- Selles et al. (2011)
  K_c = 1.34 x fractional Canopy Cover (%) - 0.1585

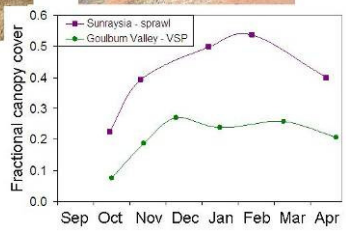
Grape K_{cb} = 1.3 *f*CC

Basal crop coefficient - K_{cb}









ET_c under 'non-standard' conditions - $ET_{c\ adj}$

$$ET_{c\ adj} = (K_{cb}.K_s + K_e)\ ET_o$$

- K_s is the stress coefficient

Maximum Allowable Depletion

MAD = RAW x D x WF

- RAW = readily available water
- D = fibrous rootzone depth
- WF = wetted fraction

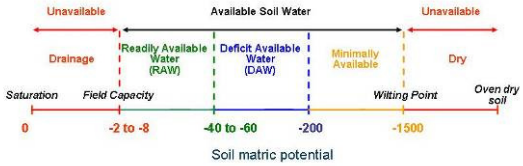




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Readily Available Water



Rootzone Depth



Wetted Fraction



Drip



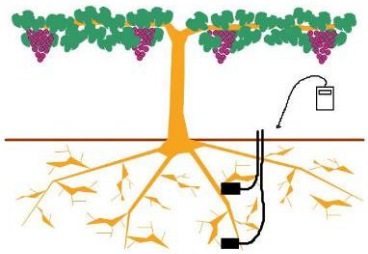
Sprinkler/Spray

Maximum Allowable Depletion

Example

- RAW = 70 mm/m
- D = 0.60 m
- WF = 0.15
  - MAD = 6.3 mm

Soil Moisture Monitoring



Soil Moisture Monitoring

- 'Soil water monitoring' handbook

www.irrigationfutures.org.au/imagesDB/news/soilwatermonitoring2ed.pdf



2. Irrigation Scheduling Tool

- Computer spreadsheet
  a) irrigation budget
  b) irrigation plan
  c) real-time scheduling
- Available from Ian Goodwin
  email: ian.goodwin@dpi.vic.gov.au
  phone: (03) 5833 5240

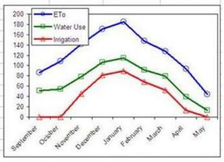
2.a) Irrigation Budget

Month	Long-term Average ETo (mm)	Canopy cover (%)	Crop Coefficient (K_{cb})	Soil Evaporation Coefficient (K_e)	Vineyard Water Use (mm)	Average Rainfall (mm)	Soil Reserve (mm)	Stress Coefficient	Irrigation Requirement (mm)
September	86	0	0.0	0.6	52	44	21	1.0	0
October	109	15	0.2	0.3	54	49	4	1.0	0
November	142	35	0.5	0.1	79	39	0	1.0	45
December	171	40	0.5	0.1	106	33	0	1.0	81
January	185	40	0.5	0.1	115	34	0	1.0	89
February	148	40	0.5	0.1	92	31	0	1.0	69
March	127	40	0.5	0.1	79	35	0	1.0	53
April	93	25	0.3	0.1	40	35	0	1.0	13
May	44	15	0.2	0.1	13	48	23	1.0	0
TOTAL (mm)					628				350
TOTAL (ML/ha)					6.3				3.5

Effective Rainfall (%) 75

Soil Water Reserve in Root-zone

Layer	Root-zone extent: Depth (mm)	Root-zone extent: Lateral (%)	Soil Texture	RAW or DAW (%)	Soil Reserve (mm)
1	300	100	clay loam	8	24
2	200	100	clay loam	8	16
3					
TOTAL	500				40



2.b) Irrigation Plan

Location	Dookie	Vine Spacing (m)	1.8
Block	south east	Row Spacing (m)	3
Variety	Chardonnay	Emitter Output (litre/hour)	1.8
Clone		Emitter Spacing (m)	0.6
Rootstock		Laterals per Row	1

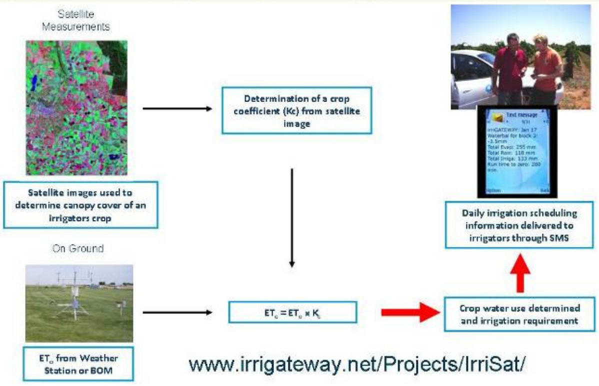
Month	Irrigation Run Time (hour)	Irrigation Amount (litre/vine)	Long-term Average ETo (mm/day)	Crop Coefficient (K_{cb})	Soil Evaporation Coefficient (K_e)	Stress Coefficient	Vine x Row Spacing (square m)	Daily Water Use (litre/vine)	Irrigation Interval (day)
September	6.5	35	2.9	0.0	0.6	1.0	5	9	4
October	6.5	35	3.6	0.2	0.3	1.0	5	10	4
November	6.5	35	4.7	0.5	0.1	1.0	5	14	2
December	6.5	35	5.7	0.5	0.1	1.0	5	19	2
January	6.5	35	6.2	0.5	0.1	1.0	5	21	2
February	6.5	35	4.9	0.5	0.1	1.0	5	17	2
March	6.5	35	4.2	0.5	0.1	1.0	5	14	2
April	6.5	35	3.1	0.3	0.1	1.0	5	7	5
May	6.5	35	1.5	0.2	0.1	1.0	5	2	15

2.c) Real-time Scheduling

Location	Dookie	Vine Spacing (m)	1.8	Minimum Effective Rainfall (mm)	10
Block	south east	Row Spacing (m)	3	Percent Effective Rainfall (%)	75
Variety	Chardonnay	Emitter Output (litre/hour)	1.8		
Clone		Emitter Spacing (m)	0.6		
Rootstock		Laterals per Row	1		

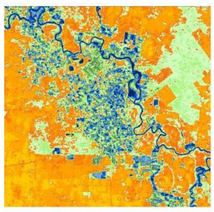
Date	Actual Rainfall (mm)	Forecast Rainfall (mm)	Effective Rainfall (mm)	Actual ETo (mm/day)	Forecast ETo (mm/day)	Canopy cover (%)	Basal Crop Coefficient K_{cb}	Soil Evaporation Coefficient K_e	Stress Coefficient	Vine x Row Spacing (square m)	Daily Water Use (litre/vine)	Soil Water Deficit (litre/vine)	Predicted Irrigation Run Time (h)	Actual Irrigation Run Time (h)	Actual Irrigation Amount (litre/vine)
24/11/10			0.0	6		40	0.5	0.1	0.9	5.4	18.1	40.8	7.6	6.5	35
25/11/10			0.0	3.2		40	0.5	0.1	0.9	5.4	9.6	15.4	2.8		0
26/11/10			0.0	4.5		40	0.5	0.1	1.0	5.4	15.1	30.4	5.6	6.0	32
27/11/10			0.0	5.1		40	0.5	0.1	1.0	5.4	17.1	17.1	3.2		0
28/11/10			0.0	4.5		40	0.5	0.1	1.0	5.4	15.1	32.1	6.0	6.5	35
29/11/10			0.0	4		40	0.5	0.1	1.0	5.4	13.4	13.4	2.5		0
30/11/10			0.0	5.5		40	0.5	0.1	1.0	5.4	18.4	31.8	5.9	6.5	35
1/12/10			0.0	5.7		40	0.5	0.1	1.0	5.4	19.1	19.1	3.5		0
2/12/10			0.0	5.5		40	0.5	0.1	1.0	5.4	18.4	37.5	6.9		0
3/12/10	18	20	6.0	4.9		40	0.5	0.1	1.0	5.4	16.4	21.5	4.0		0
4/12/10	42	30	24.0	5.9		40	0.5	0.1	1.0	5.4	19.8	0.0	0.0		0
5/12/10			0.0	6.1		40	0.5	0.1	1.0	5.4	20.4	20.4	3.8		0
6/12/10			0.0	5.8		40	0.5	0.1	1.0	5.4	19.4	39.8	7.4	6.5	35
7/12/10			0.0	3.4		40	0.5	0.1	1.0	5.4	11.4	16.1	3.0		0
8/12/10			0.0	1.9		40	0.5	0.1	1.0	5.4	6.4	22.5	4.2		0
9/12/10			0.0	4.6		40	0.5	0.1	0.3	5.4	4.6	27.1	5.0		0
10/12/10			0.0	5.6		40	0.5	0.1	0.3	5.4	5.6	32.7	6.1	6.5	35
11/12/10			0.0	4.4		40	0.5	0.1	0.3	5.4	4.4	4.4	0.8		0
12/12/10			0.0	5		40	0.5	0.1	0.3	5.4	5.0	9.4	1.7		0
13/12/10			0.0	5.4		40	0.5	0.1	0.3	5.4	5.4	14.9	2.8		0
14/12/10			0.0	5.7		40	0.5	0.1	0.3	5.4	5.7	20.6	3.8		0
15/12/10			0.0	5.5		40	0.5	0.1	0.3	5.4	5.5	26.1	4.8		0
16/12/10			0.0	5.2		40	0.5	0.1	0.3	5.4	5.2	31.3	5.8		0
17/12/10			0.0	3.7		40	0.5	0.1	0.3	5.4	3.7	35.1	6.5	6.5	35
18/12/10			0.0	4.3		40	0.5	0.1	0.3	5.4	4.3	4.3	0.8		0
19/12/10			0.0	2.6		40	0.5	0.1	0.3	5.4	2.6	6.9	1.3		0
20/12/10			0.0	3.8		40	0.5	0.1	0.3	5.4	3.8	10.7	2.0		0
21/12/10			0.0	3.5		40	0.5	0.1	0.3	5.4	3.5	14.3	2.6		0
22/12/10			0.0	4.9		40	0.5	0.1	0.3	5.4	4.9	19.2	3.6		0
23/12/10			0.0	5.7		40	0.5	0.1	0.3	5.4	5.7	24.9	4.6		0
24/12/10			0.0	6.1		40	0.5	0.1	0.3	5.4	6.1	31.0	5.7	6.0	32
25/12/10			0.0	4.2		40	0.5	0.1	1.0	5.4	14.1	14.1	2.6		0
26/12/10			0.0		5.4	40	0.5	0.1	1.0	5.4	18.1	32.1	6.0		0
27/12/10			0.0		6.3	40	0.5	0.1	1.0	5.4	21.1	53.2	9.9		0
28/12/10			0.0		6.8	40	0.5	0.1	1.0	5.4	22.8	76.0	14.1		0

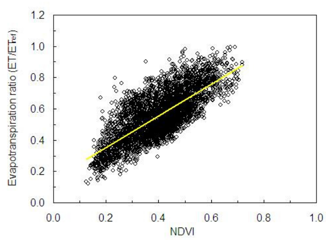
3. Future Scheduling Tools - IrriSat



www.irrigateway.net/Projects/IrriSat/

3. Future Scheduling Tools - DPI SEBAL/METRIC





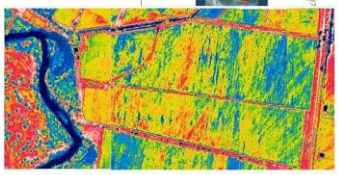
3. Future Scheduling Tools

- Bureau of Meteorology – Forecast Explorer

www.bom.gov.au/watl/index.shtml



- Thermography



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