13

Application of a New Web-Based Tool(*CropWaterUse*) for Determining Evapotranspiration and Irrigation Requirements of Major Crops at Three Locations in Queensland

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1. Introduction

Decreased water availability in many areas has created the need to make more efficient use of limited water resources. To maximize production and profits, growers need to make decisions regarding planting date, crop type, planted area, and irrigation management, which are affected by the amount of water available. Therefore, they need to know how much water is needed to grow a particular crop, which they currently estimate in most cases based on previous experience. However, crop water requirements can vary significantly, among other things, with crop type, season, location, planting date, and available water, which could make it inappropriate to extrapolate previous experiences to future planning. Also, occasionally growers may want to grow unfamiliar crops, which can further complicate planning. Growers and consultants need reliable estimates of crop water requirements to make irrigation decisions aimed at improving water use efficiency and profits. A current challenge is that growers' perception of crop water requirements for particular crops and corresponding irrigation scheduling practices are based on historical weather patterns. These weather patterns are likely to change in the future if climate change and climate variability predictions prove to be true (Howden et al., 2007; IPCC, 2007), leading to changes in planting times and crop growth patterns. Growers could benefit from new tools to help them anticipate and adapt to the effects of these potential changes.
In the last two decades there have been considerable advances in automatic weather station networks across the world and in developing improved procedures to calculate crop water use from weather data (Allen et al., 1998). However, the fact remains that most growers still do

not use weather data to make irrigation decisions. Part of the reason is that the information is not easily accessible or it is not available in the required format. In Australia, for example, daily weather data and the calculated grass-reference evapotranspiration (ETo) are available online from the Australian Bureau of Meteorology (http://www.bom.gov.au/silo/) in two types of datasets, the *Data Drill* and the *Patched Point* datasets. The *Data Drill* dataset provides interpolated data for any location in Australia and the *Patched Point* dataset combines interpolated data with Bureau of Meteorology measurements. Even though ETo data are available, for this information to be useful to growers it needs to be transformed into crop evapotranspiration (ETc) for specific crops and locations, or even further transformed into estimates of soil water status for particular fields. Growers, in general, do not have the knowledge and/or the tools to make these transformations. Therefore, there is a need to make ETc values derived from weather data accessible to growers. The availability of internet services and on-line weather databases provides new opportunities to develop and maintain web-based decision support tools for growers.

In general, growers need to make both strategic (planning) and tactical (day-to-day) irrigation and cropping system decisions. The strategic decisions concern questions such as: what crops to grow, how much area of each crop to grow, when to plant each crop, how much area of crop to irrigate and how much to grow as dryland, etc. If water is the main limiting factor, as it is in many parts of Australia, it is important to know how much water they would need to grow specific crops in a given area and planting day, which will determine how much area can be planted according to the amount of water available. The tactical decisions involve day-to-day irrigation scheduling, which determine timing and amount of irrigation to be applied to each crop during each irrigation event. Tools can be developed that use weather data to assist growers make both strategy and tactical decisions based on daily weather data. There is a long history of development of computer programs that use weather data to aid in irrigation scheduling, some recent and some dating back to the time when personal computers first became available (Abourached et al., 2007; Brown et al., 2010; Car et al., 2008; Chapman et al., 2008; Chauhan et al., 2011; Chopart et al., 2007; Cull, 1979; Davidson et al., 1998; Evett and Lascano, 1993; Fox et al., 1993; Howell et al., 1995; Inman-Bamber and Attard, 2005; Jensen, 1969; Kincaid and Heermann, 1974; McKay et al., 2009; Raes et al., 2009; Richards et al., 2008; Steduto et al., 2009; Thysen and Detlefsen, 2006).

Unfortunately, however, historically growers have been slow to adopt these tools for practical decision-making. There have been many reasons for that. In the early days, one of the main reasons was that weather data were not readily available for the different locations. Also, weather data were collected with manual weather stations, which meant that someone would have to physically travel to the station site every day to record the data. Therefore, there could be a long time lag between data collection and the time the data got to the end user, especially for stations located in remote areas. Another issue limiting the uptake of decision-support tools in the early days was the need for manual data input, which was time-consuming and tedious. With the development of electronic weather stations and the internet, some of these early issues can be overcome. However, some barriers to adoption of this technology still remain. First, there is the issue of computer illiteracy of many of the older growers who are predominantly the ones making decisions on the farm. Also, the lack of internet connectivity in many rural areas can be a problem. Additionally, there are issues relating to the way many decision-support tools have been conceived and designed. Many are just too complex for the normal grower since they have been designed as research tools, targeting scientists rather than growers, as is the case of many mechanistic crop growth models. Others have been developed as user-friendly tools, but training and on-going support for growers have been lacking. In other cases, tools have been developed for just one crop, which become of limited use for growers that have to deal with a variety of crops. Other tools have been developed for a given region, therefore cannot be applied to other regions without considerable modifications. The lack of local validation can also be an issue affecting accuracy of many tools, which contributes to failing to gain the trust of local growers.

Despite all these issues, with recent advances in technology, there are still opportunities to develop tools that would respond to the need of many growers, if an adequate process for development and adoption is followed. This chapter reports on a new web-based tool (*CropWaterUse*) recently developed in Australia by Agri-Science Queensland to help growers and crop consultants determine, among other things, daily and seasonal crop evapotranspiration and irrigation requirements, assuming full irrigation (no crop stress). The chapter presents a description of *CropWaterUse* and illustrates its application by using it to simulate evapotranspiration and irrigation requirements of several major crops grown in three different environments (cool, mild, and hot) in Queensland, Australia.

2. Description of *CropWaterUse*

CropWaterUse is a web-based tool designed to help growers and crop consultants make strategic decisions. Although it was designed for growers and crop consultants, it could have application for policy makers and water resource planning agencies that need to create policies for regulating water use and allocating water resources. The information generated by *CropWaterUse* can also be useful for irrigation engineers when designing irrigation systems, especially for unfamiliar crops and locations. It has been designed to be user-friendly and to require minimum inputs. It can assist growers in making strategic water management decisions by allowing them to easily answer the question of how much water would be needed to grow a crop at a given planting day and location. Users can compare scenarios by changing inputs. The tool can then be used to make side-by-side comparisons of different scenarios, which allow the user to answer "what if" questions. It uses historical weather data and, therefore, is not intended to be used as an irrigation scheduling tool, which would require daily real-time data. *CropWaterUse* is freely available online at http://cropwateruse.dpi.qld.gov.au.

2.1 System architecture

CropWaterUse is designed with a client-server multi-tiered architecture consisting of three tiers: client-side (presentation), server-side (logic), and server-side (data) as shown in Figure 1. It was developed using the technologies and tools shown in Table 1. All presentation logic is handled on the client-side tier. The server-side application logic interacts with a server-side SQL database that has been developed using MSSQL 9.0. Figure 2 shows the logic flowcharts for accessing the system and performing analysis.

2.2 Website statistics

CropWaterUse is capable of monitoring website statistics using the Google Analytics suite of web tools. It has the ability to provide website statistics visits using various breakdowns, including: Geo-locations, visitor loyalty, browser capabilities and traffic sources. For example, Figure 3 shows some of the website statistics produced from October 2009 to

September 2010. It shows 223 visits to the website from 17 countries, with most of the visitors coming from Australia. Since the website consists of several pages, the 223 visits have resulted in 1000 page views.

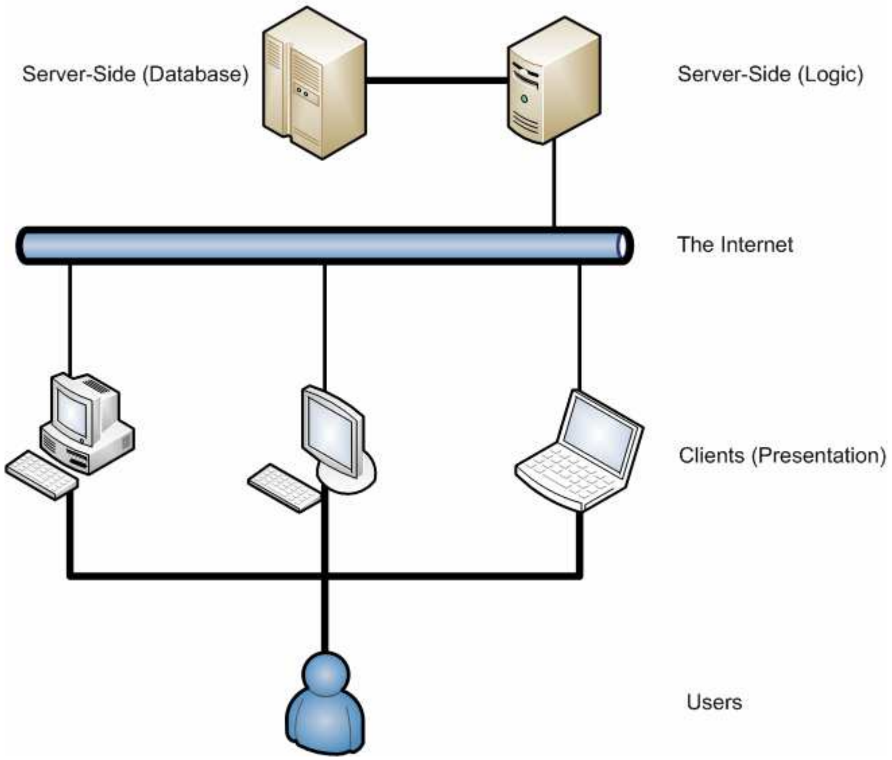


Fig. 1. Three-tier system architecture used to design *CropWaterUse*

Tool/language	**Version/comments**
Visual Studio.NET	2008
ASP.Net and C#	3.5 SP1
SQL Server	2005
TeeChart 3.0.NET	3.0 March Build
Developer Express Components ASP.NET	v.9.3+
Javascript	

Table 1. Technologies and tools used to develop *CropWaterUse*

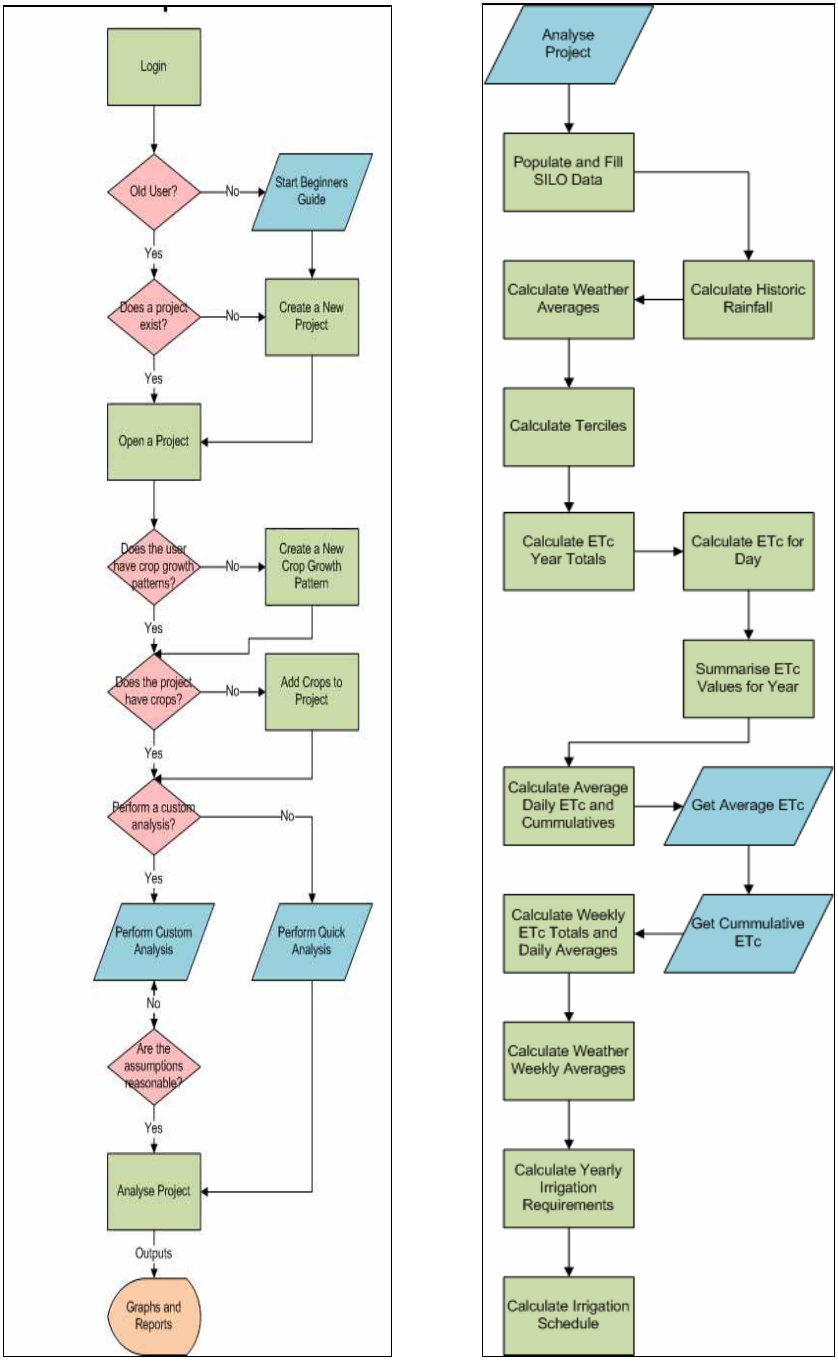


Fig. 2. Logic flowcharts for accessing the system and performing analysis in *CropWaterUse*

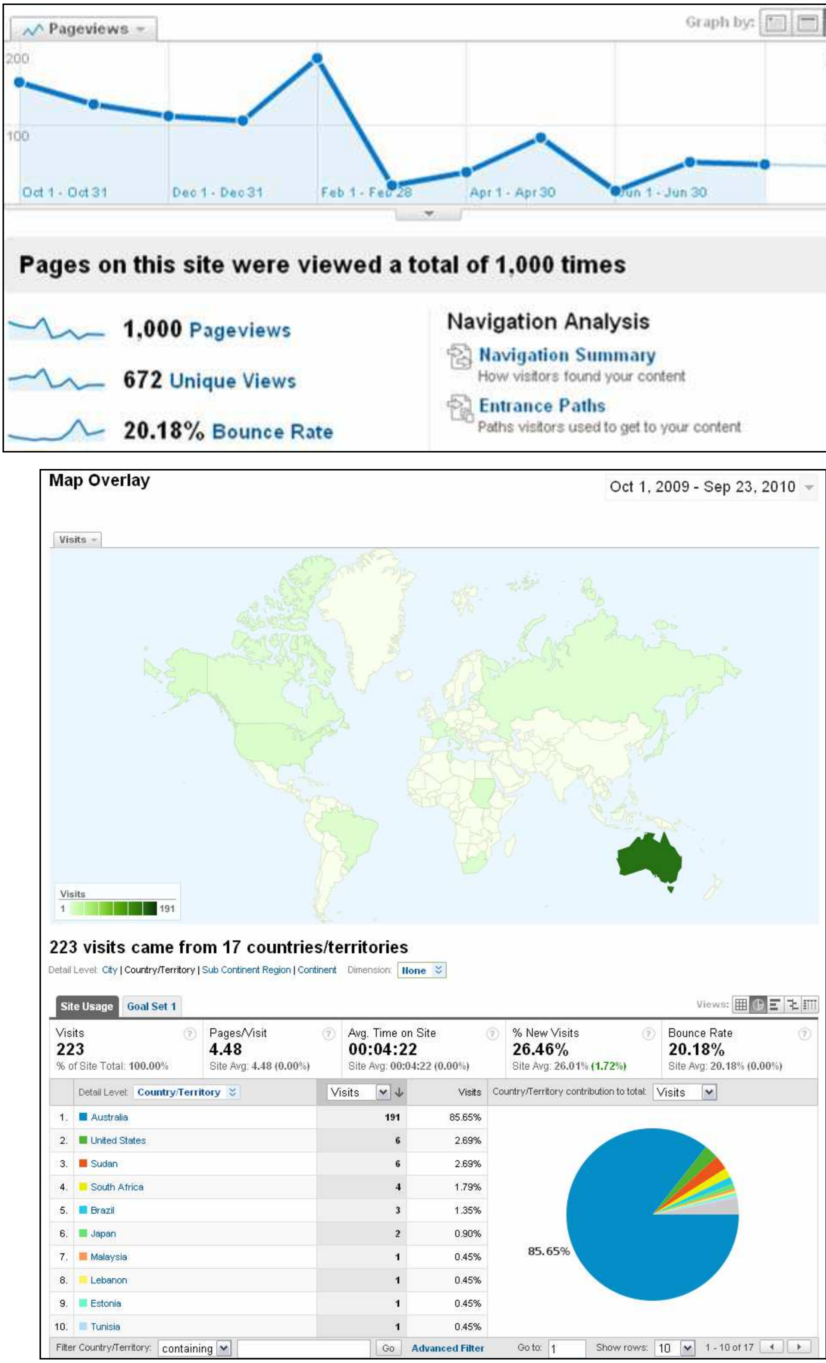


Fig. 3. Website statistics of *CropWaterUse* during October 2009 to September 2010

2.3 Inputs and analysis

Before using the system for the first time, users need to create an account, which is done online by answering a few questions. Then the system automatically sends the login information to the specified email address. After login, the next step is for the user to create a project to perform an analysis. A project consists of crops that are added to the project to create an analysis scenario. Each scenario specifies a crop type (such as cotton, corn…), which has a sowing date, location, and crop growth pattern. The crop growth pattern is the crop coefficient (Kc) curve, that is, the Kc values and the lengths of growth stages (LGS). For instance, cotton planted on 15 October at Dalby would be a scenario that can be added to the project and cotton planted on 1 November at the same location would be a different scenario. In each project, users can specify as many scenarios as needed. Projects can be saved and can be re-used or edited later and the user can also save many different projects. When an analysis is performed, outputs for each scenario in the project are produced, which allow side-by-side comparison of the different scenarios. Currently, users can choose crop growth patterns from a variety of broad-acre and horticultural crops and from many locations across Queensland and New South Wales, Australia. The number of locations is currently limited by the available weather data, but could easily be expanded by including weather data from other locations. The historical weather record for the locations available in *CropWaterUse* currently spans from 1957 to 2008.

Once scenarios are created, the user can perform either a quick analysis or a custom analysis to generate outputs. The quick analysis uses all the years in the historical weather record, an irrigation efficiency of 75%, and a soil water deficit of 75 mm to trigger irrigation events. The custom analysis allows the user to change these assumptions. However, a minimum of 10 consecutive years of weather data record needs to be included in the custom analysis to be able to generate statistics. Both types of analyses assume that the soil profile is full at sowing and that the crop is never under water stress. To facilitate its use, *CropWaterUse* includes extensive help facilities, including written step-by-step instructions, a wizard, and even an online video tutorial.

2.4 Calculations

CropWaterUse uses historical weather data to calculate daily values of crop evapotranspiration (ETc). ETc for a crop with no water stress is calculated using the FAO-56 single crop coefficient procedure as (Allen et al., 1998):

$$ETc = Kc \times ETo \qquad (1)$$

where, ETc = crop evapotranspiration (mm day^{-1}), Kc = crop coefficient (unitless) and ETo= grass-reference evapotranspiration (mm day^{-1}).

The user can specify a crop growth pattern by inputting Kc values for the initial, mid and end periods (Kc ini, Kc mid, and Kc end), and the LGS for the initial, crop development, mid-season, and late season development stages. The definitions of these stages provided by FAO-56 (Allen et al., 1998) are given in Table 1.

Growth Stage	Definition
Initial	Planting to 10% ground cover
Crop Development	10% ground cover to effective full cover
Mid-Season	Effective full cover to start of maturity
Late Season	start of maturity to harvest or full senescence

Table 2. Definitions of crop development stages given by FAO-56 (Allen et al., 1998)

For each crop, *CropWaterUse* provides default Kc values, which have been taken from FAO-56, and LGS for combinations of three generic growing environments (Cool, Mild and Hot) and crop maturity groups (Early, Medium, and Late). The LGS values were determined by local experience and by conducting simulations with the APSIM crop growth model (Keating et al., 2003). Also, lysimeter and eddy covariance measurements of ETc are currently underway to determine Kc and LGS values for local crops, which will be incorporated into *CropWaterUse* as new information becomes available. Although default values are provided for Kc and LGS, advanced users have the flexibility to change these values. In fact, the tool allows users to create new crops or new crop varieties by inputting adequate Kc and LGS values, if known. The tool calculates daily Kc values by linear interpolation between the specified values for the initial, mid and late season stages.

The historical weather data is taken from the Enhanced Meteorological Dataset available from SILO, which is part of the Department of Environmental and Resources Management (DERM) (Jeffrey et al., 2001). The enhanced dataset is interpolated from data collected by the Australian Bureau of Meteorology. *CropWaterUse* takes ETo values directly from SILO, which are calculated with the FAO-56 Penman-Montheith method (Allen et al., 1998) as:

$$\text{ETo} = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T+273} u_2\,(e_s - e_a)}{\left[\Delta + \gamma\,(1 + 0.34u_2)\right]} \tag{2}$$

where, ETo = grass-reference evapotranspiration (mm day^{-1}), Δ = slope of the saturation vapor pressure versus air temperature curve (kPa °C^{-1}), Rn = net radiation at the crop surface (MJ m^{-2} day^{-1}), G = soil heat flux density (MJ m^{-2} day^{-1}), T = mean daily air temperature at 2 m height (°C), u_2 = mean daily wind speed at 2 m height (m s^{-1}), e_s = saturation vapour pressure (kPa), e_a = actual vapour pressure (kPa), e_s – e_a = saturation vapour pressure deficit (kPa) and γ = psychrometric constant (kPa °C^{-1}). Since actual measurements of wind speed and solar radiation are not available for many sites in Australia, SILO calculates ETo using a fixed value of u_2 = 2.0 m s^{-1} and solar radiation data derived from observed cloud oktas. An evaluation of errors associated with these assumptions has been reported by Fitzmaurice and Beswick (2005).

CropWaterUse calculates daily ETc values for every day in the specified historical weather record. This information is used to calculate statistics (such as averages and measures of variability) and seasonal totals. Daily rainfall and ETc values are used to conduct a daily soil water balance to obtain an estimate of irrigation requirements, number of irrigations, and timing of each irrigation event. An estimate of water losses (runoff + deep percolation) is calculated from the soil water balance, considering the efficiency of rain and irrigation.

Growing seasons are grouped according to seasonal rainfall and are classified as “DRY”, “AVERAGE”, and “WET”, for which separate statistics for seasonal ETc, rainfall and irrigation requirements are produced. Seasons are classified into “DRY”, “AVERAGE”, and “WET” using long-term average of rainfall data, rather than using the specified analysis period. This is done to ensure that short term analyses do not portray years incorrectly against the long-term averages. The historical lowest to highest and determining the 33% and 66% indexes of the sorted values. In the output the years are colour-coded to indicate “DRY”, “AVERAGE”, and “WET” seasons.

2.4 Outputs

The system produces a series of graphical and tabular outputs that show side-by-side comparison of the different scenarios. Users are not limited to the number of scenarios they can run at one time and the graphical displays automatically expand and contract to accommodate the number of scenarios. The outputs can be printed or saved in a variety of formats (ie., xls, pdf, doc, png), which facilitates further manipulation of the data by the user. Although graphical and tabular outputs are created and displayed separately to facilitate online viewing, a compiled summary report is also produced that includes all the graphs and tables.

To illustrate some of the calculations and outputs of *CropWaterUse*, we performed a quick analysis comparing cotton (summer crop) planted on 12 November at Oakey (Queensland, Australia) and wheat (winter crop) planted on 6 June at the same location. Figure 4 shows the calculated average of daily evapotranspiration (ETc) as a function of days after sowing (DAS) for each of the two scenarios. Figure 4 only shows the average ETc for each DAS including all the years in the historical weather record. It, therefore, does not show the variability between years, which can be quite significant. Figure 5 shows the same information as Figure 4, but plotted as a function of calendar day, illustrating the fact that the growing seasons for the two crops do not overlap, since wheat is a winter crop while cotton is a summer crop. It also shows that the average peak daily ETc is about 5 mm day^{-1} and 6 mm day^{-1} for wheat and cotton, respectively. This information is vital for determining irrigation system capacity. Figure 6 shows the daily cumulative average ETc for each crop, which indicates that at that location cotton uses an average of about 670 mm of seasonal ETc while wheat only uses about 400 mm.

Figure 7 shows boxplots comparing the seasonal ETc, effective rain, and irrigation requirement for both scenarios. Boxplots are useful because they show the data divided into quartiles, which provides a measure of central tendency (such as the median), a measure of variability from season to season, and the magnitude of extreme events. Figure 7 shows that even though cotton at this location uses an average of around 670 mm, for a given season the actual value can vary between about 460 to 750 mm, the lower value probably corresponding to a very wet season and the highest value to a very dry season. It also shows a similar variability in seasonal ETc for wheat. The rainfall boxplots indicate that on average that location receives more rain during the summer than during the winter crop, with similar variability among seasons for the two crops. Because it depends on both ETc and rain, the irrigation requirement inherits even more variability from season to season than ETc and rain. Figure 7 shows that at that location, cotton requires anywhere from 300 mm to 750 mm of irrigation while wheat requires from about 100 to about 520 mm. This is a huge variability, which highlights the need to employ irrigation scheduling techniques that allow the grower to adapt irrigation management to changing weather conditions. In this regards, there is a need for further development of weather forecasting technology, for the short and medium time scale, and the integration of weather forecast information into irrigation decision-support tools.

In addition to the graphical outputs, *CropWaterUse* produces tabular outputs. Figure 8 shows a sample summary output produced by *CropWaterUse* for the cotton and wheat scenarios at Oakey. The summary shows the seasonal statistics, including the minimum, maximum, average, and standard deviation for the calculated variables for each scenario. These outputs also show the assumptions that were used to generate those numbers, such as the analysis period, crop, location, irrigation efficiency, growth pattern (Kc and LGS), soil water deficit to trigger irrigation and sowing date.

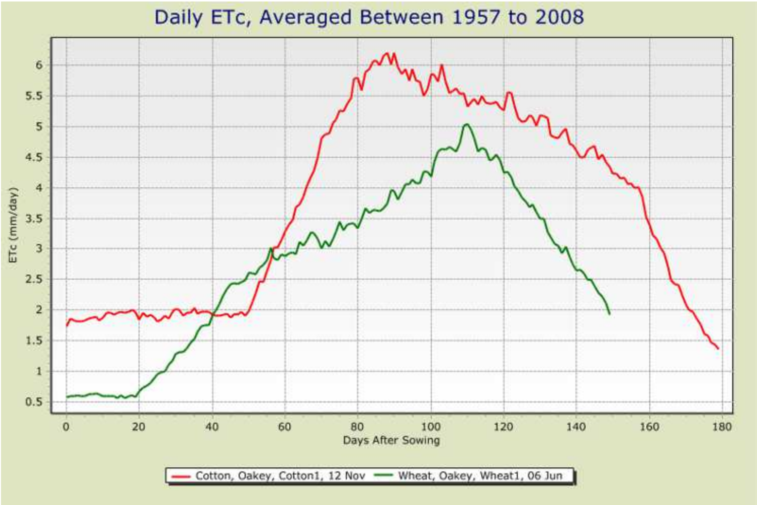


Fig. 4. Calculated average daily crop evapotranspiration as a function of days after sowing for cotton and wheat at Oakey

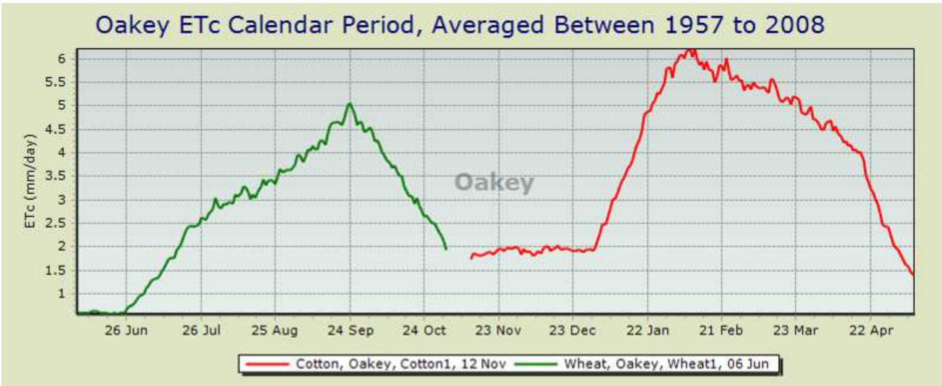


Fig. 5. Calculated average daily crop evapotranspiration as a function of calendar day for cotton and wheat at Oakey

Figure 9 shows a sample weekly weather and crop water use output produced by *CropWaterUse*. It shows the averages of the weather data that was used to calculate ETo and ETc for each week of the growing season for each scenario. Figure 10 shows a sample of the irrigation requirement output for each year included in the analysis. It includes seasonal ETc, rainfall, rainfall losses, final soil water deficit (at the end of the season), irrigation demand, and irrigation required (taking into account the irrigation efficiency). Figure 11 shows a sample output for irrigation timing for each year in the analysis period. The last column in the table shows the number of irrigations required during each year. Years for the irrigation requirement and irrigation timing outputs are colour-coded to represent "DRY", "AVERAGE", and "WET" seasons. Separate summary statistics are shown for the "DRY", "AVERAGE", and "WET" seasons (Figure 12).

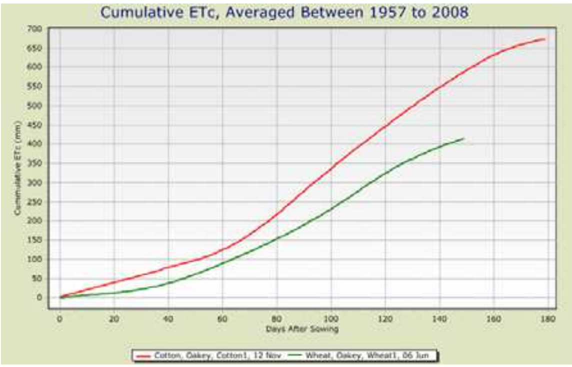


Fig. 6. Calculated average daily cumulative crop evapotranspiration as a function of days after sowing for cotton and wheat at Oakey

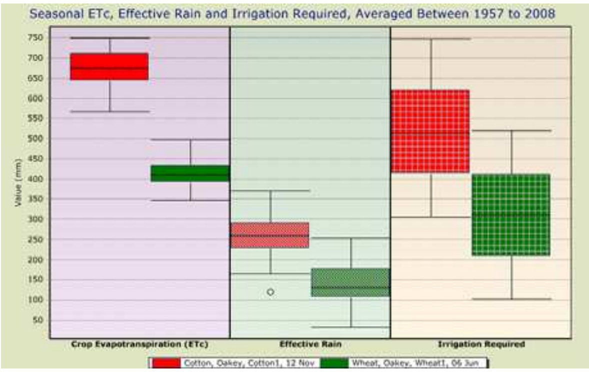
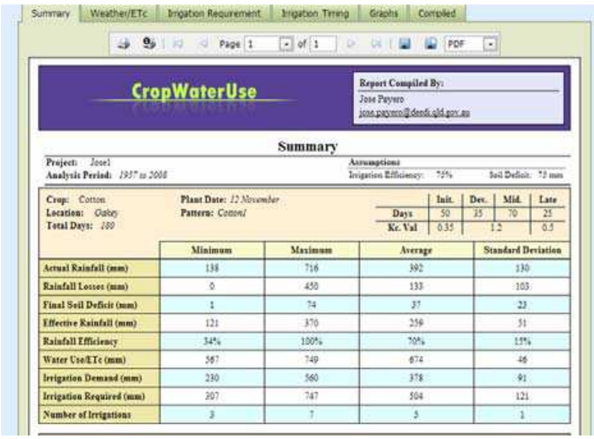


Fig. 7. Boxplot of seasonal crop evapotranspiration, effective rain, and irrigation requirement for cotton and wheat at Oakey



CropWaterUse

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Summary

Project: Jose1
Analysis Period: *1957 to 2008*

Assumptions
Irrigation Efficiency: 75% Soil Deficit: 75 mm

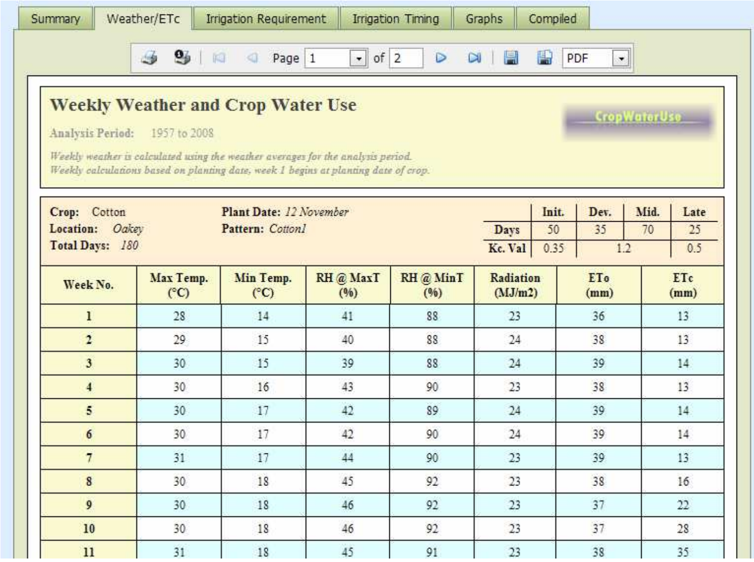
Crop: Cotton
Location: *Oakey*
Total Days: *180*

Plant Date: *12 November*
Pattern: *Cotton1*

	Init.	Dev.	Mid.	Late
Days	50	35	70	25
Kc. Val	0.35	1.2		0.5

	Minimum	Maximum	Average	Standard Deviation
Actual Rainfall (mm)	138	716	392	130
Rainfall Losses (mm)	0	450	133	103
Final Soil Deficit (mm)	1	74	37	23
Effective Rainfall (mm)	121	370	259	51
Rainfall Efficiency	34%	100%	70%	15%
Water Use/ETc (mm)	567	749	674	46
Irrigation Demand (mm)	230	560	378	91
Irrigation Required (mm)	307	747	504	121
Number of Irrigations	3	7	5	1

Fig. 8. Sample summary output produced by *CropWaterUse*



Weekly Weather and Crop Water Use

Analysis Period: 1957 to 2008

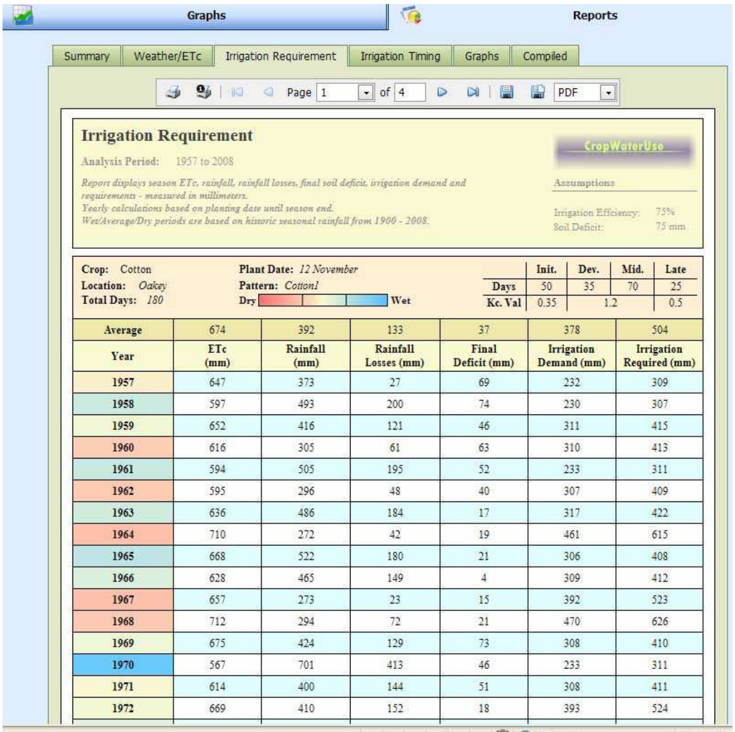
Weekly weather is calculated using the weather averages for the analysis period.
Weekly calculations based on planting date, week 1 begins at planting date of crop.

Crop: Cotton
Location: *Oakey*
Total Days: *180*
Plant Date: *12 November*
Pattern: *Cotton1*

	Init.	Dev.	Mid.	Late
Days	50	35	70	25
Kc. Val	0.35	1.2		0.5

Week No.	Max Temp. (°C)	Min Temp. (°C)	RH @ MaxT (%)	RH @ MinT (%)	Radiation (MJ/m2)	ETo (mm)	ETc (mm)
1	28	14	41	88	23	36	13
2	29	15	40	88	24	38	13
3	30	15	39	88	24	39	14
4	30	16	43	90	23	38	13
5	30	17	42	89	24	39	14
6	30	17	42	90	24	39	14
7	31	17	44	90	23	39	13
8	30	18	45	92	23	38	16
9	30	18	46	92	23	37	22
10	30	18	46	92	23	37	28
11	31	18	45	91	23	38	35

Fig. 9. Sample Weekly weather and crop water use output produced by *CropWaterUse*



Irrigation Requirement

Analysis Period: 1957 to 2008

Report displays season ETc, rainfall, rainfall losses, final soil deficit, irrigation demand and requirements - measured in millimeters.
Yearly calculations based on planting date until season end.
Wet/Average/Dry periods are based on historic seasonal rainfall from 1900 - 2008.

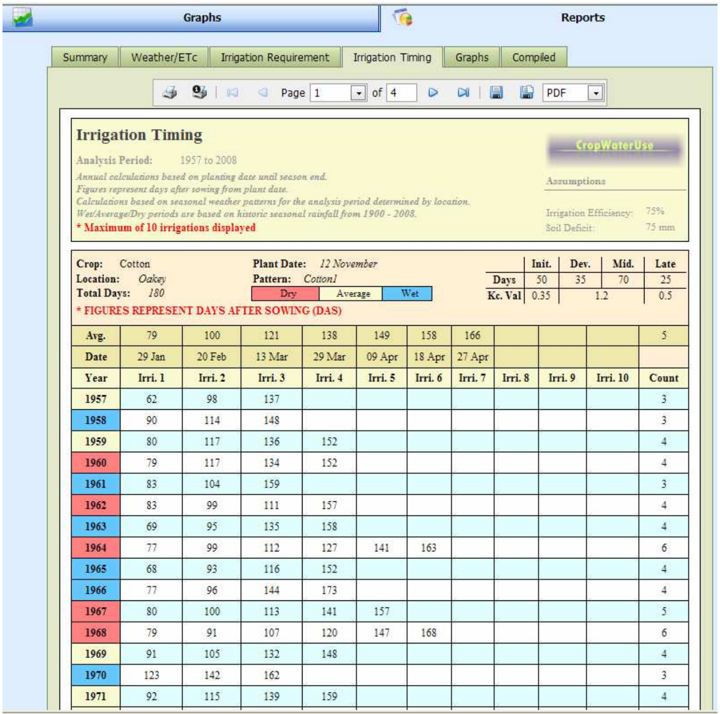
Assumptions
Irrigation Efficiency: 75%
Soil Deficit: 75 mm

Crop: Cotton
Location: *Oakey*
Total Days: *180*
Plant Date: *12 November*
Pattern: *Cotton1*
Dry – **Wet**

	Init.	Dev.	Mid.	Late
Days	50	35	70	25
Kc. Val	0.35	1.2		0.5

Year	ETc (mm)	Rainfall (mm)	Rainfall Losses (mm)	Final Deficit (mm)	Irrigation Demand (mm)	Irrigation Required (mm)
Average	674	392	133	37	378	504
1957	647	373	27	69	232	309
1958	597	493	200	74	230	307
1959	652	416	121	46	311	415
1960	616	305	61	63	310	413
1961	594	505	195	52	233	311
1962	595	296	48	40	307	409
1963	636	486	184	17	317	422
1964	710	272	42	19	461	615
1965	668	522	180	21	306	408
1966	628	465	149	4	309	412
1967	657	273	23	15	392	523
1968	712	294	72	21	470	626
1969	675	424	129	73	308	410
1970	567	701	413	46	233	311
1971	614	400	144	51	308	411
1972	669	410	152	18	393	524

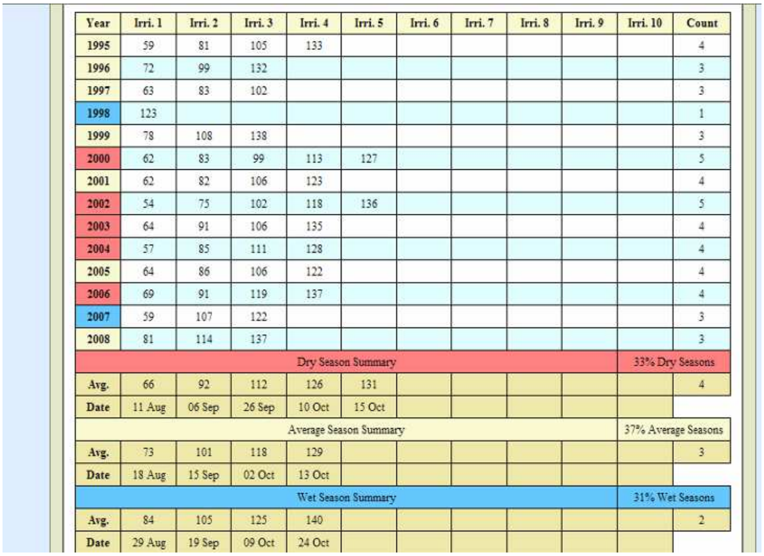
Fig. 10. Sample irrigation requirement output produced by *CropWaterUse*



	Init.	Dev.	Mid.	Late
Days	50	35	70	25
Kc. Val	0.35	1.2		0.5

Avg.	79	100	121	138	149	158	166				5
Date	29 Jan	20 Feb	13 Mar	29 Mar	09 Apr	18 Apr	27 Apr				
Year	Irri. 1	Irri. 2	Irri. 3	Irri. 4	Irri. 5	Irri. 6	Irri. 7	Irri. 8	Irri. 9	Irri. 10	Count
1957	62	98	137								3
1958	90	114	148								3
1959	80	117	136	152							4
1960	79	117	134	152							4
1961	83	104	159								3
1962	83	99	111	157							4
1963	69	95	135	158							4
1964	77	99	112	127	141	163					6
1965	68	93	116	152							4
1966	77	96	144	173							4
1967	80	100	113	141	157						5
1968	79	91	107	120	147	168					6
1969	91	105	132	148							4
1970	123	142	162								3
1971	92	115	139	159							4

Fig. 11. Sample irrigation timing output produced by *CropWaterUse*



Year	Irri. 1	Irri. 2	Irri. 3	Irri. 4	Irri. 5	Irri. 6	Irri. 7	Irri. 8	Irri. 9	Irri. 10	Count
1995	59	81	105	133							4
1996	72	99	132								3
1997	63	83	102								3
1998	123										1
1999	78	108	138								3
2000	62	83	99	113	127						5
2001	62	82	106	123							4
2002	54	75	102	118	136						5
2003	64	91	106	135							4
2004	57	85	111	128							4
2005	64	86	106	122							4
2006	69	91	119	137							4
2007	59	107	122								3
2008	81	114	137								3
Dry Season Summary										33% Dry Seasons	
Avg.	66	92	112	126	131						4
Date	11 Aug	06 Sep	26 Sep	10 Oct	15 Oct						
Average Season Summary										37% Average Seasons	
Avg.	73	101	118	129							3
Date	18 Aug	15 Sep	02 Oct	13 Oct							
Wet Season Summary										31% Wet Seasons	
Avg.	84	105	125	140							2
Date	29 Aug	19 Sep	09 Oct	24 Oct							

Fig. 12. Sample summary of average irrigation timing for Dry, Average and Wet seasons produced by *CropWaterUse*

3. Example application of *CropWaterUse*

3.1 Description of simulations

To illustrate the usefulness of *CropWaterUse* we conducted two simulations (studies) for hypothetical cropping scenarios. In the first study, simulation runs using default assumptions for irrigation efficiency of 75% and irrigation trigger of 75 mm of soil water deficit was compared with improved irrigation efficiency of 85% and increased soil water deficit of 100 mm. Also, comparison of variety and planting date combinations including early maturing/early planted and late maturing/late planted summer grain crops, including sorghum, corn, soybeans, mungbeans and sunflowers in relatively cooler and hotter climatic conditions of Dalby and Emerald, respectively (Fig. 13).

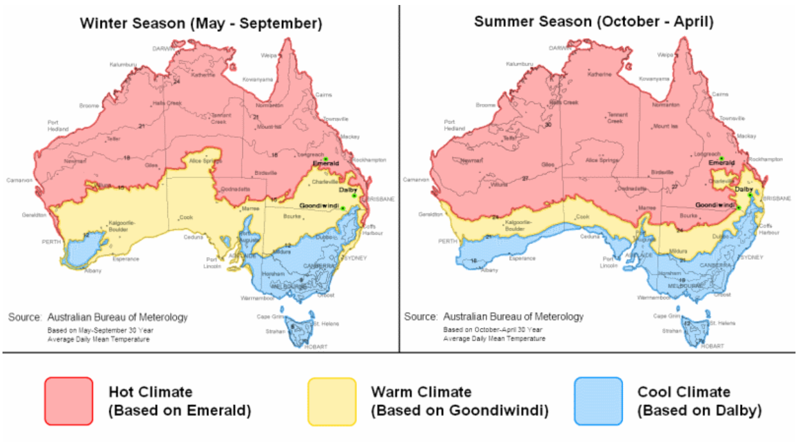


Fig. 13. Relatively hotter, warmer and cooler climatic regions in Australia based on seasonal minimum and maximum temperatures in Emerald, Goondiwindi and Dalby in Queensland.

Early planting of sorghum, corn and sunflower was parameterized at 30 Sept, whereas for soybeans and mungbeans at 30 Oct. Late planting of all crops was considered at 30 Jan. In this study, parameterisation of maturity type, crop duration, critical growth stages (initial, development, mid and late) and Kc value required for only 3 growth stages (Kc ini, Kc mid, and Kc end) are given in Table 3. These values can be changed in the tool (user defined) if they are known for a location and crop type.

In the second study we conducted simulations of evapotranspiration and irrigation requirements of early and late-planted cotton (summer crop) and wheat (winter crop) grown in three locations in Queensland, Australia. The locations were selected to represent cool, mild, and hot environments and included Dalby, Goondiwindi and Emerald. The current planting windows for cotton and wheat at these locations are October to November and May to June, respectively. We compared crop water use patterns and irrigation requirements for cotton planted early (September 15) and late (November 15), and for wheat planted early (April 15) and late (June 15) for all three locations. Simulations with *CropWaterUse* were performed using default values for rainfall efficiency (75%), irrigation efficiency (75%) and trigger irrigation deficit (75 mm). Parameterization of maturity type, length of growth stages (initial, development, mid and late) and Kc values (Kc ini, Kc mid, and Kc end) for cotton and wheat at three regions (Dalby, Goondiwindi, Emerald) is given in Table 4.

		Maturity	Crop	Growth stages (days)				Kc		
Crops	Regions	type	Duration (days)	Initial	Development	Mid	Late	Kc ini.	Kc mid	Kc end
Sorghum	Dalby	Early	120	20	30	40	30	0.40	1.20	0.50
		Late	130	20	35	45	30	0.40	1.20	0.50
	Emerald	Early	110	20	30	35	25	0.40	1.25	0.50
		Late	120	20	30	45	25	0.40	1.25	0.50
Maize	Dalby	Early	125	20	30	30	25	0.40	1.20	0.50
		Late	135	20	35	40	30	0.40	1.20	0.50
	Emerald	Early	115	20	20	25	20	0.60	1.25	0.50
		Late	120	20	25	30	25	0.60	1.25	0.50
Soybean	Dalby	Early	130	20	25	60	25	0.40	1.20	0.50
		Late	140	20	30	65	25	0.40	1.20	0.50
	Emerald	Early	95	15	15	50	15	0.40	1.20	0.50
		Late	105	15	20	55	15	0.40	1.20	0.50
Mungbean	Dalby	Early	85	15	20	25	25	0.40	1.15	0.30
		Late	95	15	25	30	25	0.40	1.15	0.30
	Emerald	Early	65	10	15	20	20	0.40	1.15	0.30
		Late	70	10	15	25	20	0.40	1.15	0.30
Sunflower	Dalby	Early	130	30	20	60	20	0.40	1.20	0.50
		Late	140	30	25	60	25	0.40	1.20	0.50
	Emerald	Early	95	15	15	50	15	0.40	1.20	0.50
		Late	105	15	20	55	15	0.40	1.20	0.50

Table 3. Parameterization of maturity type, crop duration, critical growth stages (initial, development, mid and late) and Kc value required for only three growth stages (Kc ini, Kc mid, and Kc end) used for this study

		Maturity	Crop	Growth stages (days)				Kc		
Crops	Regions	type	Duration (days)	Initial	Development	Mid	Late	Kc ini.	Kc mid	Kc end
Cotton	Dalby	Early	180	50	35	70	25	0.35	1.20	0.50
	Goondiwindi	Early	170	45	30	70	25	0.35	1.20	0.50
	Emerald	Early	130	35	25	65	20	0.35	1.20	0.50
Wheat	Dalby	Early	140	15	30	55	40	0.30	1.15	0.40
	Goondiwindi	Early	140	15	30	55	40	0.30	1.15	0.40
	Emerald	Early	115	10	25	45	35	0.30	1.15	0.40

Table 4. Parameterization of maturity type, crop duration, critical growth stages (initial, development, mid and late) and Kc value (Kc ini, Kc mid, and Kc end) for cotton and wheat at three regions

3.2 Results of simulations

3.2.1 First Study: early maturity/early planted vs. late maturity/late planted summer grain crops

Crop ETc decreased significantly (about 100 mm on average across crops and locations) when agronomic conditions were changed from early maturity/early planted to late maturity/late planted systems for both (cooler and hotter) climatic conditions (Fig. 14). Sorghum, soybeans, maize and sunflower had significantly greater seasonal ETc than mungbeans, which had the lowest (340 mm). Sunflower, mungbeans and soybeans had significantly greater seasonal ETc at Dalby than at Emerald, whereas Sorghum had higher ETc at Emerald than at Dalby (Fig. 14).

At Dalby, early maturing/early planted grain crops appeared to receive considerably more rainfall than the late maturity/late planted grain crops (Table 5). On average, early maturity/early planted crops received about 90 mm more rain than the late maturity/late planted crops. Among early maturity/early planted crops, mungbeans received the least rainfall, somewhere between 40 mm and more than 100 mm less than the other crops, whereas this difference with late maturity/late planted crop was less than 50 mm for mungbeans (Table 5).

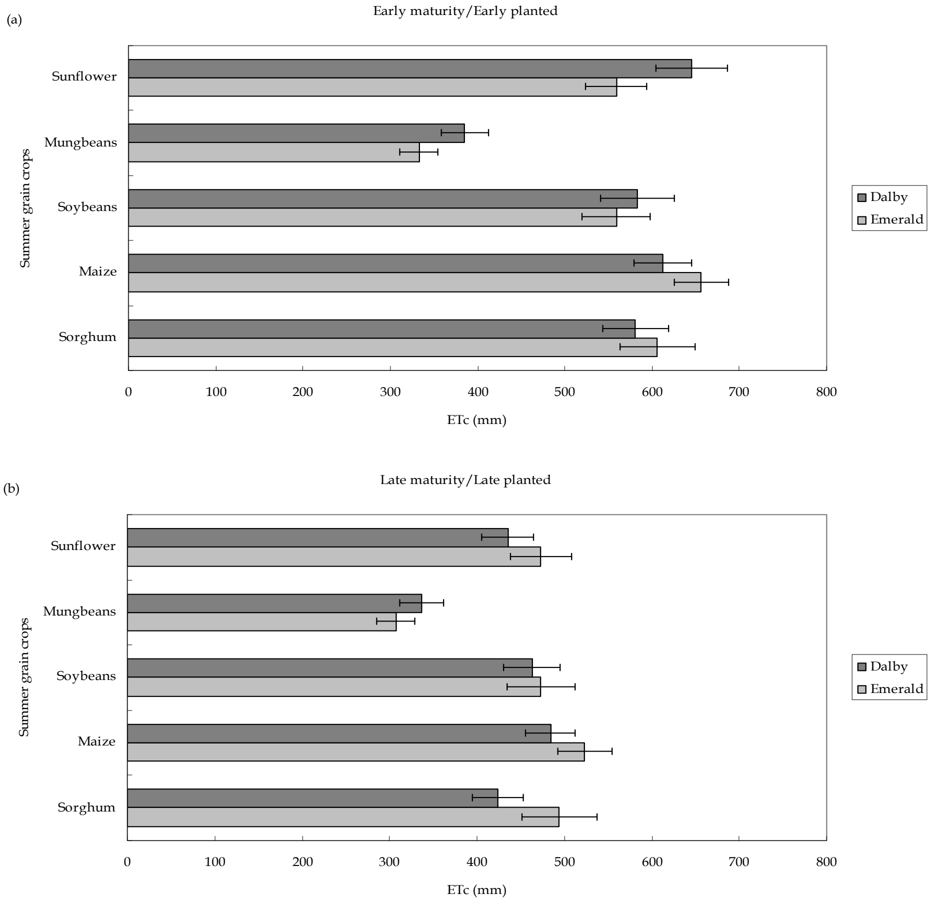


Fig. 14. Range of crop evapotranspiration (ETc) as estimated by the *CropWaterUse* tool using historical weather data (1957-2008) for "fully irrigated" sunflower, mungbeans, soybeans, maize and sorghum for various scenarios (a) early planting, early maturing varieties, and (b) late planting, late maturing varieties in cooler (at Dalby) and hotter (at Emerald) climatic conditions in Queensland. Bar indicates +/- standard deviation

Runoff+deep drainage losses of rainfall water varied between 60 mm and 100 mm for early maturity/early planted crops, whereas this loss was around 70 mm to 85 mm for late maturity/late planted crops. Rainfall efficiency was between 70% and 80% for both scenarios at Dalby.
Increasing irrigation efficiency by 10% (from 75% to 85%) and soil water deficit about 25 mm (from 75 mm to 100 mm) resulted in one less irrigation event required for all crops whether

	Summer grain crops in cooler climate (Dalby)				
Planting/Irrigation Parameters	Sorghum	Maize	Soybeans	Mungbeans	Sunflower
Early maturing, early planted					
Rainfall (mm)	299 (97)	265 (82)	343 (107)	227 (76)	333 (110)
Runoff+deep drainage (mm)	73 (56)	61 (50)	112 (78)	65 (49)	97 (70)
Rainfall Efficiency (%)	78 (13)	79 (14)	70 (16)	74 (15)	73 (14)
Irrigation Requirement (mm)					
At 75% eff., 75 mm deficit	437 (116)	343 (111)	532 (126)	260 (86)	505 (122)
At 85% eff., 100 mm deficit	367 (112)	289 (97)	431 (115)	203 (87)	407 (111)
Number of irrigation					
At 75% eff., 75 mm deficit	4 (1)	3 (1)	5 (1)	3 (1)	5 (1)
At 85% eff., 100 mm deficit	3 (1)	2 (1)	4 (1)	2 (1)	3 (1)
Late maturing, late planted					
Rainfall (mm)	209 (97)	203 (95)	219 (101)	172 (90)	219 (101)
Runoff+deep drainage (mm)	75 (77)	74 (78)	77 (76)	68 (71)	84 (81)
Rainfall Efficiency (%)	71 (21)	70 (22)	71 (19)	69 (23)	68 (21)
Irrigation Requirement (mm)					
At 75% eff., 75 mm deficit	346 (87)	336 (90)	386 (94)	268 (80)	360 (86)
At 85% eff., 100 mm deficit	294 (81)	280 (91)	324 (84)	219 (85)	300 (84)
Number of irrigation					
At 75% eff., 75 mm deficit	3 (1)	3 (1)	4 (1)	3 (1)	4 (1)
At 85% eff., 100 mm deficit	2 (1)	2 (1)	3 (1)	2 (1)	3 (1)

Table 5. Pattern of rainfall, losses through runoff+deep drainage, irrigation requirement and number of irrigation as estimated from the *CropWaterUse* tool (using historical weather data from 1957-2008) for a range of scenarios, early maturing/early planted and late maturing/late planted, for sorghum, maize, soybeans, mungbeans and sunflower in cooler climatic conditions at Dalby, Queensland. Values in parenthesis indicate standard deviation

planted early or late. However, late maturity/late planted sorghum, soybeans and sunflower required one irrigation less than the early maturity/early planting, there was no change in the number of irrigations for maize and mungbeans. Across the growing conditions, soybeans and sunflower needed 3-5 irrigations, whereas sorghum, maize and mungbeans required 2-4 irrigations for the relatively cooler conditions at Dalby.

At Emerald, there was only about 10 mm difference in rainfall between early maturity/early planted and late maturity/late planted scenarios (Table 6). On average, Emerald received about 56 mm less rainfall water than Dalby in the growing season stretching from October to April. Runoff+deep drainage losses for early planted crops ranged between 30 and 70 mm, whereas losses were between 70 and 90 mm for late planted crops. Improving irrigation efficiency by 10% (from 75% to 85%) and increasing water deficit by 25 mm (from 75 mm to 100 mm) decreased the number of irrigations for all crops for both scenarios, except for mungbeans, which required a minimum of 2 irrigations. Sorghum and maize at Emerald required one extra irrigation for various scenarios (early vs. late planting, unimproved irrigation efficiency/smaller deficit vs. improved irrigation efficiency/larger water deficit) than Dalby (Table 6).

In the first study, seasonal ETc for various summer grain crops as influenced by planting decision and irrigation management practices were compared between relatively cooler and hotter climatic regions in Queensland. While using the *CropWaterUse* tool, we tested two strategies to understand the irrigation water requirements. One strategy was to plant early in the season with a quick-maturing variety, this may reduce the number of irrigations, and another strategy was to slightly improve the irrigation efficiency and delay the irrigation with a slightly greater soil water deficit.

	Summer grain crops in hotter climate (Emerald)				
Planting/Irrigation Parameters	Sorghum	Maize	Soybeans	Mungbeans	Sunflower
Early maturing, early planted					
Rainfall (mm)	259 (102)	170 (85)	206 (90)	168 (74)	206 (90)
Runoff+deep drainage (mm)	68 (66)	34 (43)	48 (57)	50 (49)	48 (57)
Rainfall Efficiency (%)	63 (22)	85 (15)	81 (16)	75 (18)	81 (16)
Irrigation Requirement (mm)					
At 75% eff., 75 mm deficit	515 (119)	428 (100)	498 (114)	259 (76)	498 (114)
At 85% eff., 100 mm deficit	427 (105)	357 (93)	431 (108)	200 (79)	431 (108)
Number of irrigation					
At 75% eff., 75 mm deficit	5 (1)	4 (1)	5 (1)	2 (1)	5 (1)
At 85% eff., 100 mm deficit	4 (1)	3 (1)	4 (1)	2 (1)	4 (1)
Late maturing, late planted					
Rainfall (mm)	216 (115)	186 (96)	193 (100)	157 (85)	193 (100)
Runoff+deep drainage (mm)	94 (26)	76 (76)	83 (76)	72 (74)	83 (76)
Rainfall Efficiency (%)	63 (22)	67 (22)	64 (21)	63 (25)	64 (21)
Irrigation Requirement (mm)					
At 75% eff., 75 mm deficit	455 (103)	421 (94)	442 (98)	253 (67)	442 (98)
At 85% eff., 100 mm deficit	388 (103)	340 (93)	364 (97)	205 (740	364 (97)
Number of irrigation					
At 75% eff., 75 mm deficit	5 (1)	4 (1)	4 (1)	2 (1)	4 (1)
At 85% eff., 100 mm deficit	3 (1)	3 (1)	3 (1)	2 (1)	3 (1)

Table 6. Pattern of rainfall, losses through runoff+deep drainage, irrigation requirement and number of irrigations as estimated using *CropWaterUse* for a range of scenarios, early maturing/early planted and late maturing/late planted, for sorghum, maize, soybeans, mungbeans and sunflower in hotter climatic conditions at Emerald, Queensland. Values in parenthesis indicate standard deviation

The ETc was about 100 mm more for the early maturity/early planted than the late maturity/late planted crops at both cooler and hotter climatic conditions (Fig. 14). This may be due to increasing evaporative demand with increasing temperature and greater in-crop rainfall between the Oct to Jan growing period for early planted crops (Table 5 and 6). Whereas the effective growing period for the late planted crops between Feb and May would have cooler conditions towards maturity of the crops, it was though expected that the hotter conditions at Emerald would lead to greater ETc than the cooler conditions at Dalby. But opposite to this, ETc for sunflower and soybeans was greater at Dalby than at Emerald, particularly for early maturity/early planted crops (Fig. 14). However, for the late maturity/late planted crop, ETc at Emerald appeared to be slightly greater than at Dalby, but differences were not significant.

Hotter conditions at Emerald compared with Dalby may increase total soil evaporation but not necessarily total crop transpiration, as hotter conditions may also advance crop maturity

(Muchow, Sinclair and Bennett 1990; Boote and Sinclair 2006), thus reducing the duration of crop growth significantly. Secondly, significantly less in-crop rainfall at Emerald than Dalby may have also contributed to reduce ETc at Emerald, particularly for early maturity/early planted crops. Rainfall differences between Dalby and Emerald were minimal for the late maturity/late planted crops, this may have resulted in slightly greater ETc for late maturity/late planted crops with hotter conditions at Emerald than at Dalby (Fig. 14).

Differences in seasonal conditions with greater rainfall, higher temperature or reduced maturity, had variable impact on the number of irrigations required for various crops. Sorghum and corn and to some extent mungbeans required one less irrigation at Dalby than at Emerald for early or late planted and with improved or unimproved irrigation efficiency and increased irrigation deficit. There was no change in number of irrigations required for soybeans and sunflower due to seasonal differences between Dalby and Emerald (Table 4 and 5).

In addition to seasonal conditions, planting time and maturity of crop can also influence the amount of in-crop rainfall, directly influencing the amount and frequency of irrigations, particularly in the cooler climatic conditions at Dalby. The early maturity/early planted crops planted in September, with a growing season of 3-4 months received about 90 mm more rainfall than the late planted crops planted in January (Table 5). This resulted in one less irrigation for most of the summer grain crops, saving water and increasing profitability. Anecdotal evidence also suggests that early-planted sorghum crops, in particular, produce higher yields than late-planted sorghum in southeast and southwest Queensland. On the other hand, there was minimal difference in the amount of in-crop rainfall between early and late planted crops at Emerald (Table 6). It should also be noted that factors such as crop vigour, soil fertility and soil depth would also influence the number of irrigations. For example, newer varieties of sorghum do not have as much crop vigour as older varieties, requiring less irrigation.

Seasonal conditions, planting time and maturity of a crop/variety may interact and complicate irrigation requirement and scheduling decisions, whereas slightly improved irrigation efficiency and increased soil water deficit to trigger irrigations are likely to have a significant impact on reducing the number of irrigations. For example, improved irrigation efficiency and increasing soil water deficit slightly resulted in one less irrigation for most of the crops, subjected to variable planting, maturity or seasonal conditions (Table 5 and 6).

3.2.2 Second study: early and late planted cotton and wheat at three locations in Queensland

The average rate of irrigation water use in Queensland has been estimated (ABS., 2007/08) at 3.1 ML/ha and 4.9 ML/ha for wheat and cotton, respectively (Figure 15). Changing the planting strategy in order to adapt to future climatic change (predicted for earlier planting of these crops) is likely to result in change in irrigation water use due to expected changes in in-crop rainfall and ETc.

For the summer crop (cotton), the simulation results showed that ETc would increase if the planting of cotton is brought forward to an earlier planting in September from November at all 3 locations (Table 7). The increase in ETc with cotton planted in mid September would be due to greater overall increase in temperature over the duration of the cotton season. Since there was not much difference in the in-crop seasonal rainfall, an additional irrigation would be needed for the early-planted cotton at all sites (Table 7).

For the winter crop (wheat), in contrast, early planting would considerably decrease ETc (Table 8), decreasing the number of irrigations from 4 to 3 at Dalby and Goondiwindi, and from 5 to 3 at Emerald. This analysis, however, does not consider the impact of early planting on crop yield, the danger of frost, or the practicality of early planting.

Among the three locations, Goondiwindi has the highest and Emerald has the lowest irrigation demand for cotton. On the other hand, Emerald has the highest irrigation demand for wheat. On average, cotton requires about 350 mm more water than wheat. The loss of water through runoff and deep drainage is also 80 mm more for cotton compared to wheat.

In summary, earlier planting of wheat at these three locations would result in less demand on irrigation water, whereas earlier planting of cotton would increase irrigation demand. This type of simulation can be performed using *CropWaterUse* in just a few minutes, and it is the type of information that can be used by growers for long-term planning.

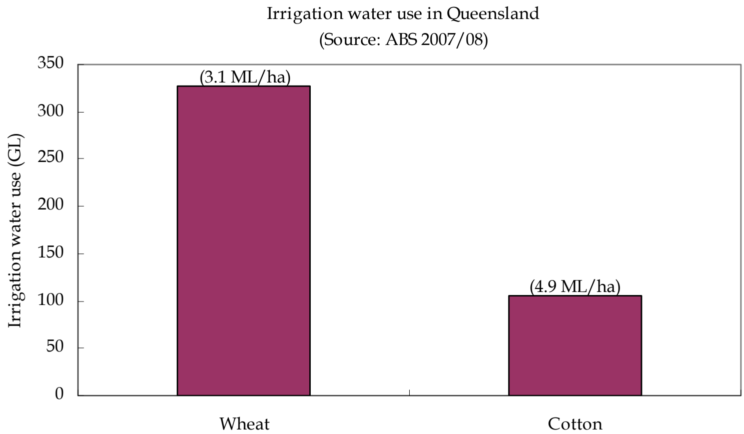


Fig. 15. Total and per hectare (ha) irrigation water use for wheat and cotton in Queensland, Australia

Parameters	Dalby		Goondiwindi		Emerald	
	Sep 15	Nov 15	Sep 15	Nov 15	Sep 15	Nov 15
Evapotranspiration (mm)	834 (50)	732 (45)	862 (48)	774 (48)	705 (42)	661 (48)
Rainfall (mm)	424 (126)	386 (129)	357 (135)	347 (144)	291 (116)	362 (139)
Runoff+Drainage (mm)	133	136	96	104	85	131
Irrigation Demand (mm)	543 (107)	482 (84)	601 (116)	531 (108)	499 (85)	430 (110)
No. of Irrigation	7 (1)	6 (1)	8 (1)	7 (1)	6 (1)	5 (1)
Dry seasons (%)	33	39	29	33	27	33
Normal seasons (%)	35	27	35	31	39	39
Wet seasons (%)	31	33	37	35	33	27

Table 7. Comparing water requirement for early (September) and late (November) planted cotton at Dalby, Goondiwindi, and Emerald, based on historical weather data (1957-2008). Values in brackets are one standard deviation

Parameters	Dalby		Goondiwindi		Emerald	
	Apr 15	Jun 15	Apr 15	Jun 15	Apr 15	Jun 15
Evapotranspiration (mm)	331 (27)	482 (50)	332 (78)	495 (53)	362 (25)	466 (33)
Rainfall (mm)	161 (81)	205 (76)	178 (94)	194 (84)	117 (82)	93 (75)
Runoff+Drainage (mm)	31	57	40	45	22	10
Irrigation Demand (mm)	201 (66)	334 (81)	194 (61)	346 (74)	267 (56)	383 (73)
No. of Irrigation	3 (1)	4 (1)	3 (1)	4 (1)	3 (1)	5 (1)
Dry season (%)	35	27	35	33	29	38
Normal season (%)	33	40	35	33	33	31
Wet season (%)	33	33	31	35	38	31

Table 8. Comparing water requirement for early (April) and late (June) planted wheat at Dalby, Goondiwindi, and Emerald, based on historical weather data (1957-2008). Values in brackets are one standard deviation

4. Conclusions

Water scarcity is becoming one of the major challenges agricultural production in Australia and in many other parts of the world is facing. Competition for limited water resources is increasing between agricultural, domestic, industrial and environmental uses. Environmental use has especially become a formidable competitor for water resources in the last two decades, as more and more regulations are put in place to protect water courses and habitats for endangered species. Since agriculture is usually the major user of fresh water resources diverted from rivers and pumped from groundwater, agricultural producers will likely face increasing social pressures to increase crop water productivity. These social pressures will be eventually translated into regulations that further restrict the use of water for agricultural production. At the same time that irrigation water is becoming scarce and more costly for growers, human population continues to grow. Therefore, agriculture will have to sustain more people, with about the same land area and with less water. Because of this, to maximize profits and sustain an increasing population with limited water, growers will have to become more creative on how they allocate water among competing enterprises and how they manage water within each enterprise on a day-to-day basis. This is a formidable task, which will demand using our ingenuity to develop new technologies and tools to assist growers make better decisions in regards to allocation of resources within the farm, including land, water, nutrients, chemicals, labour, machinery, capital, etc. New and improved tools and skills will be needed to assist growers in managing individual resources, such as water, and also for integrating, harmonising, and optimising the use of all the resources that contribute to agricultural production as a whole system, rather than as collection of disparate components.

In this chapter we have presented the description and application of *CropWaterUse,* a new web-based tool that has been developed in Australia to help growers plan the use of water, one of the many components of the agricultural production system. The system was developed with feedback from many growers and crop consultants, mainly located in the cotton producing areas of eastern Australia. Growers and consultants were involved in the development and testing of *CropWaterUse*, with the aim of developing a system that answered questions that were relevant to them and that, at the same time, was user-friendly. Since its release in October 2009, the system has had a positive uptake by producers, consultants, and even policy makers. To promote uptake, the system has been supported by extension and research personnel located in different agricultural areas of Queensland, including Dalby, Emerald, Kingaroy, Gatton, and Toowoomba. To continuously improve the tool, there is also ongoing research aimed at improving the way we calculate ETc for different crops and as new research knowledge is gained, it will be incorporated into *CropWaterUse*. In this regards, *CropWaterUse* will also serve as an effective extension tool since research information is immediately made available to end users, avoiding the usual time lag that occurs within the research-extension-adoption process.

Since it has been designed as a simple tool, it is recognised that *CropWaterUse* has some limitations. One of the limitations is that it does not deal with crop stress. This is an important limitation for dryland and deficit-irrigation production. Another important limitation of *CropWaterUse* is that it uses LGS, needed to construct the crop growth patterns (i.e. Kc curves), in "days" rather than "cumulative growing degree days (CGDD)." That can have an important impact on season length when comparing the same crop grown in areas with significantly different weather conditions. We tried and overcome this limitation by providing default LGS values for three growing environments and three maturity groups for each crop. However, better information on Kc curves based on CGDD's rather than "days" is needed for the different crops and growing environments. Another limitation is that it does not deal with different plant populations or with different planting configurations, such as the different types of skip-row configurations that are commonly used by Australian growers.

Despite its limitations, *CropWaterUse* can be a useful planning tool for growers and crop consultants, if used for the intended purpose and with appropriate Kc and weather data. A more comprehensive new tool is now under development that will complement the capabilities of *CropWaterUse*. The new tool will be aimed at assisting growers in day-to-day irrigation scheduling, rather than long-term planning. Therefore, it will use daily near-real-time weather data, rather than just historical data. It will use the dual Kc approach detailed in FAO-56, rather than the single Kc used in *CropWaterUse*. The dual Kc considers the effect of crop stress and the impact of rain and irrigation on evaporation from the soil surface. It will also integrate economic analysis and weather forecasting into the day-to-day irrigation decision-making process.

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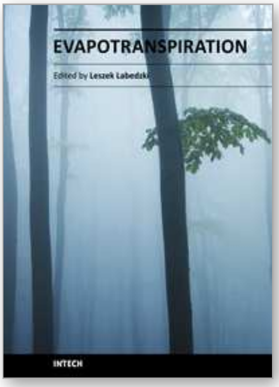

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Evapotranspiration is a very complex phenomenon, comprising different aspects and processes (hydrological, meteorological, physiological, soil, plant and others). Farmers, agriculture advisers, extension services, hydrologists, agrometeorologists, water management specialists and many others are facing the problem of evapotranspiration. This book is dedicated to further understanding of the evapotranspiration problems, presenting a broad body of experience, by reporting different views of the authors and the results of their studies. It covers aspects from understandings and concepts of evapotranspiration, through methodology of calculating and measuring, to applications in different fields, in which evapotranspiration is an important factor. The book will be of benefit to scientists, engineers and managers involved in problems related to meteorology, climatology, hydrology, geography, agronomy and agricultural water management. We hope they will find useful material in this collection of papers.

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