Cotton Catchment Communities CRC

FINAL REPORT

Part 1 - Summary Details

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Background

The current drought in Australia is focussing attention on the use of water by the irrigation sector within Australia. The Cotton industry has been specifically targeted as a gross user of water. The industry needs to pull together the currently known information on how water is used by the industry and the benefits that this has for regional communities and the nation as a whole. In addition it needs to demonstrate the improvements in irrigation management that have occurred and are continuing to be implemented by the industry in response to the limited water situation that it finds itself in. At the same time it needs to be confident that it is managing water efficiently and can monitor the on-going improvement in management resulting from the R,D &E effort into improving irrigation management in the industry. The industry needs to ensure that it is implementing World's Best Practice in irrigation management and can demonstrate this to the Australian community.

Objectives

There were primarily two objectives to the project:

1. Collate and publish existing information on irrigation management benchmarks within the Australian Cotton industry. The following draft report was prepared:

   Payero, J.O. and Harris, G.A. 2007 Benchmarking water management in the Australian Cotton Industry, Cotton Catchment Communities CRC/Dept of Primary Industries and Fisheries, Toowoomba

2. Implement strategies to gather and report on cotton industry water management benchmarks in an on-going fashion to monitor performance of the industry.

Two reporting products produced as a result of this project:

- The Water Benchmark Tool – a web-based tool hosted through the Cotton BMP website and accessible by irrigators
- ISID – Irrimate Surface Irrigation Database – developed to store Irrimate Surface Irrigation Evaluations and report summary information from these evaluations.

Methods

To address Objective 1 a draft report prepared collating the existing research and industry information on water use efficiency within the cotton industry. It can be used by the industry to document its use and management of irrigation water at the national, farm and field scale. It will present this information in context with all Australian irrigation sectors and benchmark performance with its international competitors. Research included will be that by Hearn, Constable, Keefer, Cull, Tennakoon, Milroy, Smith, Dalton and Raine together with international literature. Data will also be drawn from the Australian Bureau of Statistics, the Rural Water Use Efficiency Projects, Boyce Comparative Analysis and Darling Downs Irrigated Crops competitions.

Objective 2 was addressed through the following activities:

2.1 The collection and reporting of water use efficiency data for as many as possible of the original 25 irrigation farms surveyed by Sunnil Tennakoon and Steve Milroy during the 1996/97, 1997/98 and 1998/99 seasons. The aim is to ascertain if their WUE has improved and what measures have been put in place since 1997 to improve irrigation management.

2.2 Development of a user-friendly database for the processing and reporting of Irrimate surface irrigation evaluations. This database can be used to report the performance of surface irrigation evaluations at the industry level into the future (whilst retaining anonymity of irrigators having had Irrimate surface irrigations performed).

2.3 A survey of existing users of HydroLOGIC to identify those using this software and the acquisition of this data which can be compiled on an industry basis. This could provide useful data at the field scale but will be dependent on the extent to which users have been using HydroLOGIC as a recording tool for their irrigation management.

2.4 Follow-up of growers who accessed the incentive scheme funds under the Rural Water Use Efficiency Incentive and those who participated in the Irrigator of the Year Awards to document case studies that highlight the Best Practice Management of irrigation by the industry. Similar case studies should be possible from NSW through the Advancing Water Management in NSW Project (and documented through the NPSI Knowledge Management project).

2.5 Collation of data from growers identified as having useful water management data sets through the Cotton BMP PCA process. This could involve Cotton Australia GSMs identifying the growers worth approaching by the Cotton CRC Water Team members to compile their data which can be reported at an industry level and as case studies.

2.6 Investigate the existence of Crop Competition datasets within each cotton valley and compiling this into a dataset that can be used to assess WUE in the industry. This has already been done for the Darling Downs but the existence of other similar datasets is at present unknown. Additional information may also be available from the National Cottongrower competitions conducted by the Australian Cottongrower - this will be investigated.

Results

Objective 1

The review Payero, J.O. and Harris, G.A. 2008 “Benchmarking Water Management in the Australian Cotton Industry” was completed and is attached at Appendix 1. Below is a summary of the review.

Introduction

The current drought is focussing the Australian community’s attention on the use of water by the irrigation sector. The Cotton Industry has been specifically targeted through extensive coverage in the media as a gross user of water. In response the industry needs to evaluate its current irrigation water use and management in order to respond in a factual way to this criticism and identify opportunities for further irrigation management improvements.

As part of this process there is a need to collate the current information on water use by the industry and the benefits it has for regional communities and for the nation. In addition it is necessary to demonstrate the improvements in irrigation management that have occurred and are continuing to be implemented by the industry. At the same time the industry needs to be confident that it is making every possible effort to manage water as efficiently as possible and monitor the on-going improvements resulting from its past and current investments in water management R, D&E. Therefore, a benchmarking process has been initiated, which is intended to help the industry evaluate the impact of its investments in water management programs and to identify priorities for future investments. This document provides an overview of some of the benchmarking concepts, reviews some of the cotton water use efficiency data obtained in Australia and overseas, and offers guidance on improving water use efficiency.

Benchmarking water management

Benchmarking agricultural water management, however, is a difficult process. A common way of benchmarking agricultural water management is by calculating how much “yield” is produced per unit “water”. This seems quite simple, but it can be very ambiguous and misleading since there is not widely accepted national or international standard on how “yield” and “water’ are measured and reported.

The term “yield” is sometimes measured as “total dry mass” or just as “harvestable yield.” For cotton, harvestable yield is either reported as “lint” or “seed” yield. The “water” term could also mean “irrigation”, “irrigation + rain”, “irrigation + rain + soil water”, or “evapotranspiration.” The “water” term can either be measured or estimated using techniques with different levels of accuracy, and could be measured at different scales (district, farm gate, or field scale). Additional ambiguities result from the fact that rain in some cases can mean “total rain,” and in others, “effective rain,” and in some cases it is measured on site, and in others it is measured at a weather station located a long distance from the farm, which can make a huge difference. Also, irrigation in some cases means “irrigation applied”, and in others, “effective irrigation” or “irrigation infiltrated.”

In addition, the ratio “yield/water” is known by different names by different people, even when calculated the same way. Terms in the literature include “*water use efficiency*,” “*irrigation water use efficiency*,” “*crop water productivity*,” etc. In this document, the term **water use efficiency (WUE)** is used, which in general is the ratio of some measure of output (usually crop yield or $) to some measure of water input (i.e. irrigation, total water, evapotranspiration).

Due to the lack of a national or international standard regarding the definition and calculation of WUE, the National Program for Sustainable Irrigation launched a consultation process to develop a national WUE framework to be proposed as a standard for Australia. Under this framework, WUE does not have a specific meaning, but is used as a generic term for a series of more specific irrigation performance indicators referred to as “*water use indices (WUI)*.” The most common indices used in Australia are defined in Table 1.

Table 1. Definition of water use efficiency indices.

Index	Name	Definition [a]	Units
GPWUI	Gross production water use index	$\frac{\text{Total product (bales) [b]}}{\text{Total water applied (ML) [c]}}$	bales/ML
IWUI (Applied)	Irrigation water use index	$\frac{\text{Total product (bales)}}{\text{Irrigation water applied (ML)}}$	bales/ML
CWUI	Crop water use index	$\frac{\text{Total product (bales)}}{\text{Evapotranspiration (ML)}}$	bales/ML

[a] These definitions were taken from Purcell and Currey (2003). Here, however, the total product is given in “bales” and all water variables are given in “ML”. In the original source, they used “kg” instead of “bales” and some of the water variables were given in “mm” and others in “ML”.

[b] Variables can also be given in a “per unit area” basis. For instance, Total product can be given in bales/ha, and Total water applied in ML/ha, which will result in the same units of bales/ML for the IWUI (Applied).

[c] Total water applied includes irrigation, water stored in the soil profile at sowing, and effective rainfall.

Challenges for effective benchmarking

It has been suggested that the cotton industry has probably gone close to doubling its WUE over the last decade mainly by increasing yield per unit area (bales/ha), and a new challenge to “*double again the WUE by 2015*” has recently been proposed. Some important questions are:

- Where is the industry now in terms of WUE and how does it compare to other water users – nationally and internationally?
- How is the industry going to know when the WUE has doubled?
- What tools and processes does the industry have to capture, analyse and report WUE information?

Many Australian cotton farmers and crop consultants currently measure their water use and calculate WUE. Results from a recent survey within the cotton industry (Doyle and Coleman, 2007) indicated that a large proportion of farmers responded “Yes” when asked if they calculated WUE in terms of bales/ML (Fig. 1),

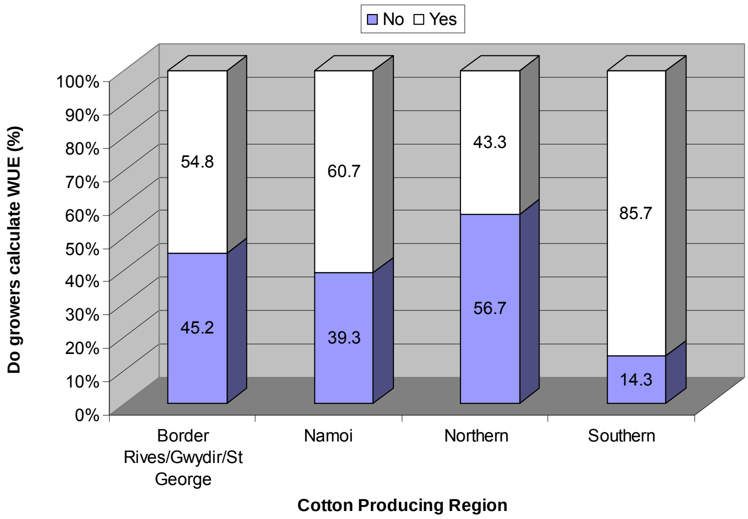

Figure 1. Volume Response to “Do growers calculate water use efficiency (WUE) in terms of bales/ML?” by region for the 2005-06 season. Data was obtained from a survey for cotton producers conducted by Doyle and Coleman (2007).

The first step towards effective benchmarking is to define “exactly” what it is that the industry should pursue. A possible, and ambiguous, objective could be to simply “increase or double WUE.” However, in the range in which crop yields respond to additional water, increasing WUE can be achieved in many ways by changing either or both of its components (yield and water) as indicated in Table 2. Again, in this context, the term “water” can mean irrigation, in-crop water inputs (rain + irrigation), water use (evapotranspiration), total water (rain + irrigation + soil water), etc.

Table 2. Effect of changes in yield and water on water use efficiency

	Water		
Yield	Constant	increase	Decrease
Constant	⇔	⇓	⇑
Increase	⇑	⇑⇔⇓	⇑
Decrease	⇓	⇓	⇑⇔⇓

“⇑”= increase, “⇔” = constant, “⇓’ = decrease, and “⇑⇔⇓” = can increase, stay constant, or increase depending on the relative magnitude of changes in yield and water.

It is important to define how the increase in WUE is going to be accomplished since it can have implications about the need for investing in the development of new technologies (via research projects) or in the application of available ones (via extension projects). Also, how the increase in WUE is going to be achieved could affect the willingness of people to participate in the process. For instance, if increases in WUE are to be achieved by using less water, it then becomes necessary to decide in the early stages of the process what is going to happen with the water that is "saved." If farmers can keep the water that they save, then they will be more likely to invest in water saving technologies.

Another important issue is to clearly define if the objective is to increase a biophysical water use index or an economic one. If the objective is to increase a biophysical water use index, then it is necessary to decide which one of either the CWUI (yield/ET), the GPWUI (yield/total water), or the IWUI (yield/irrigation) will be targeted. This is important because if the objective is to increase CWUI, then it can be done by fully-irrigating (or even by over-irrigating) to obtain the maximum potential yield.

Also, since in a fully-irrigated situation the ET component cannot be significantly modified by management, then the strategy should be to increase yield potential by other means like plant breeding, nutrient management, etc. On the other hand, if the objective is to maximize the GPWUI or the IWUI, wasting water by over-irrigating should then be avoided, and strategies to minimize water inputs while increasing or maintaining yields should be applied.

Instead of having the objective of increasing WUE (bales/ML), the industry could have a purely economic objective, such as increasing some measure of economic returns (i.e. profits, net return, gross margins, etc) per unit irrigation ($/ML), per unit area ($/ha), or for the whole farm ($/farm), which could require a different strategy than just increasing the bales/ML. The economic objective to increase economic returns could also involve considering the benefits of growing other crops, or including them in crop rotations with cotton where and when practical.

Given the current water scarcity and environmental concerns that affect irrigated agriculture in many parts of the world, irrigated agriculture may need to adopt a new paradigm based on the economic objective of maximizing net economic benefits rather than the biological objective of maximizing yield per unit area. However, irrigation to maximize economic benefits is a substantially more complex and challenging problem than just meeting crop water requirements to produce maximum yield, since both biological and economic factors need to be considered in the analysis. It should then be recognized that water management strategies needed for maximizing profitability ($/ML) (considering environmental sustainability) do not necessarily coincide with those needed for maximizing the bales/ML or bales/ha.

In 2006, due to a combination of high grain prices and low cotton prices, an economic analysis in the cotton producing areas conducted by Wylie (2006) showed that profit per unit irrigation ($/ML) was higher for grain crops (sorghum, maize, and wheat) compared to cotton, especially under cool growing environments. He also showed considerable economic benefits of including grain crops in rotation with cotton. The high grain prices were mainly due to increased demand for grains to be used in ethanol production.

Gross returns per unit irrigation for some of the key irrigation industries in Australia are: Horticulture ($1400/ML), Sugar ($960/ML), Cotton ($360/ML), Rice ($160/ML), and Pasture ($100/ML) (ABS statistics 1992-96). Of course, as attractive as other enterprises may seem from the economic standpoint, for a variety of reasons not all farmers have the flexibility or the desire to totally change enterprises or include other crops in rotation with cotton. Also, agricultural enterprises require specific environments, technology, infrastructure, markets, and culture, and therefore are not easily interchangeable.

Figure 2. Aerial photograph showing farm storages (“ring tanks”) on the Darling Downs,

Another challenge for effective benchmarking is the need to use the appropriate index based on a clearly stated objective. If the objective is to compare performance across regions and seasons, indices that allow these comparisons need to be selected. For example, a common approach for benchmarking is to use indices that are based on irrigation water applied such as the IWUI (Applied). This index, however, has the shortcoming that it can vary significantly for different regions and seasons since there is not unique relationship between crop yield and irrigation applied.

Figure 2 shows relationships for cotton obtained at Emerald, which illustrates that the relationship varies with season depending on in-crop rainfall and other factors, and the data for the 1983-84 season shows that during wet years, irrigation may not be needed and could even decrease yields. It shows the typical curvilinear response functions often reported for situations in which irrigation applied ranged from deficit-irrigation to over-irrigation. The curvilinear response to irrigation results from application of excess water, some of which could be lost by runoff, deep percolation and evaporation, and some could just stay unused in the soil profile after the crop is harvested.

The curvilinear response could also result from yield reduction by excess water due to factors like nutrient leaching or water logging. In should be kept in mind, however, that over-irrigation is actually desirable in situations in which a leaching fraction needs to be applied to prevent salt build-up in the soil profile. Also, over-irrigation can sometimes occur even with good water management due to the variable nature of rainfall events. Crop yield increases approximately linearly with irrigation in situations in which the crop is not over-irrigated, water is not wasted by low irrigation efficiencies, and irrigations are properly scheduled.

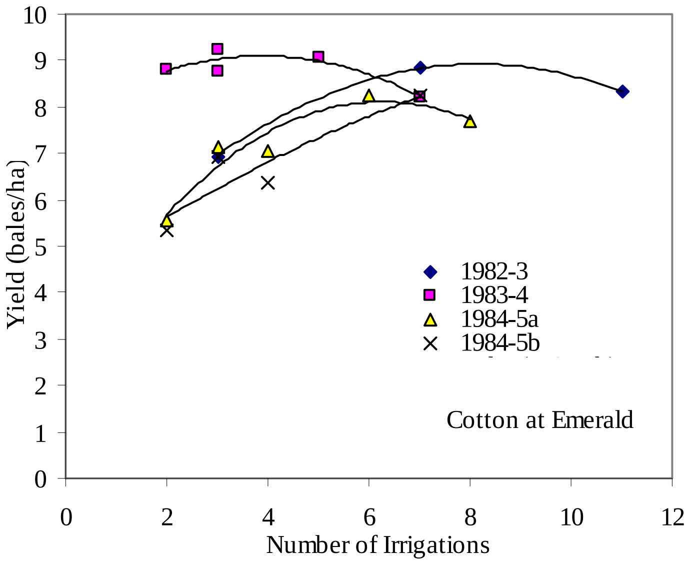

Figure 3. Cotton lint yield as a function of number of irrigations obtained at Emerald during three seasons. Adapted from data reported by Keefer (No date).

In most agricultural regions and seasons, the yield response to irrigation usually has a positive intercept, that is, there is usually some yield (dry land yield) even with no irrigation due to in-crop rainfall and water stored in the soil profile at sowing. In arid regions, however, the dry land yield could be zero and, in some very dry areas and seasons it may even take a considerable amount of irrigation before a marketable yield can be obtained.

Water use efficiencies in the Australian cotton industry

Several studies have evaluated irrigation performance in the Australian cotton industry. Following is a summary of WUE obtained with various systems.

WUE from alternative irrigation systems in Australia

Data from farmer's fields comparing IWUI from alternative irrigation systems in Australia have been reported by Raine and Foley (2002). They estimated cotton IWUI values by surveying farmers using different irrigation systems. They reported average and range IWUI values for subsurface drip irrigation (SDI), traditional furrow, and large mobile irrigation machines (LMIMs – centre pivots and lateral moves) (Table 3).

Table 3. Irrigation water use index (bales/ML of irrigation) values for different irrigation systems obtained from farmer's survey conducted by Raine and Foley (2002).

	Irrigation System		
	SDI	Traditional Furrow	LMIMs
Range	1.5-2.75	0.6-1.6	1.35-2.6
Average	2.4	1.0	1.9

SDI = Subsurface drip irrigation, LMIMs = lateral move irrigation machines

Since IWUI can vary significantly from year to year, IWUI values always need to be interpreted with caution. However, data in Table 3 should serve the purpose of comparing the performance of the different irrigation systems. As expected, the range of values was very wide for all irrigation systems. Also, as expected, the highest average IWUI was obtained with SDI, followed by the LMIMs, and the lowest with the traditional furrow system. This order reflects the potential irrigation efficiencies that can be achieved with the different irrigation systems, with the more efficient irrigation systems having the higher IWUI values.

It is good to notice that changing from traditional furrow to LMIMs almost doubled the IWUI, and changing to SDI produced an additional increase in IWUI of almost 150% over traditional furrow. Although this improvement could probably be achieved in practice, the question is if it is economically feasible to change to more efficient irrigation systems. Factors to consider should not only be their water-saving potential, lower labour requirements, low environmental impact, potential for higher yield from reduced water logging, but also their high initial investment. The industry should also consider that some improvements can still be made by optimising traditional furrow irrigation systems, and also by improving irrigation scheduling.

WUE from alternative management of sprinkler irrigation

An experiment comparing alternative management of large mobile irrigation machines to irrigate cotton on the Darling Downs was conducted by White and Raine in the 2002/03 season. They compared several Regulated Deficit Irrigation (RDI) and Partial Rootzone Drying (PRD) treatments. They were not able to reach a conclusion about the potential of PRD to improve WUE due to the low irrigation frequencies applied and to the amount and timing of in-crop rain, but they obtained valuable data from the RDI treatments. They found that cotton yields were maximized by applying 50% of the irrigation water that was normally applied commercially using a lateral move irrigation machine, which corresponded to replacing around 79% of potential evapotranspiration (ETo). No yield response was obtained by applying more than 50% of the irrigation applied in commercial applications.

These results suggest potential improvement in the way commercial operations manage these machines. These results point out that these machines can save water if they are managed correctly, but they can waste as much water as a surface system if managed incorrectly. The IWUI values from this study varied with irrigation treatment between 0.88 and 1.17 bales/ML and averaged 1.0 bales/ML (Table 4).

Figure 3 shows that the IWUI increased significantly when irrigation increased from 25 to 50% of commercial practice, but linearly declined as additional water was applied. Based on the decreasing tendency of IWUI with irrigation amount previously shown from other datasets, it is odd that in this study the IWUI increased when irrigation increased from 25 to 50% of irrigation applied compared to commercial practice.

Table 4. Irrigation water use index (IWUI = lint yield/irrigation) for cotton irrigated by a lateral move irrigation machine in the Darling Downs (Adapted from White and Raine, 2004).

% ETo Replaced by Irrigation	Irrigation (% of commercial)	IWUI (bales/ML)
71	25	0.99
79	50	1.17
86	75	1.00
93	100	0.94
100	125	0.88
Average		1.00

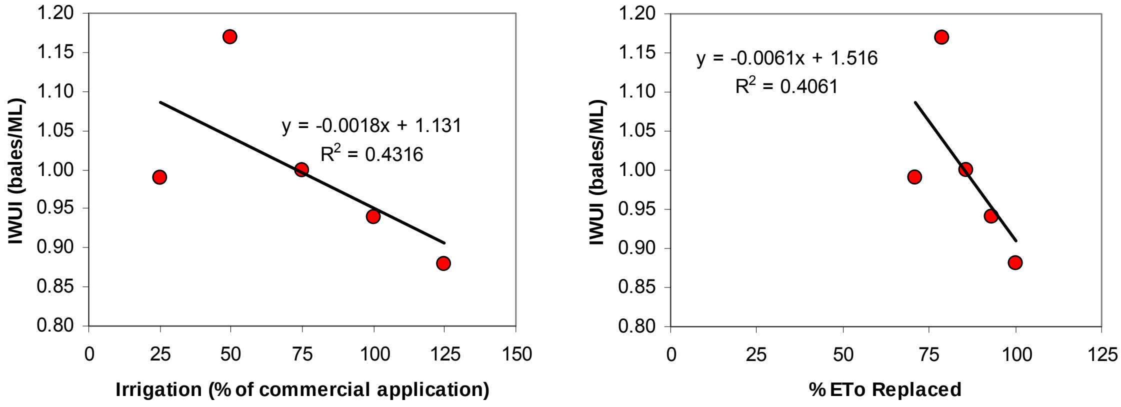

Figure 3. Irrigation water use index (IWUI = lint yield/irrigation) for cotton irrigated by a lateral move irrigation machine in the Darling Downs as a function of irrigation applied and % of potential evapotranspiration (ETo) replaced by irrigation. Adapted from White and Raine (2004).

WUE from commercial SDI and furrow systems

Data comparing cotton IWUI and GPWUI from subsurface drip irrigation (SDI) and furrow irrigation systems from commercial fields at Biloela, and from demonstration fields at Dalby and Moree are shown in Table 5. In general, SDI resulted in higher IWUI and GPWUI values by increasing yields, reducing water use, or both. On average for all site-years, the IWUI for SDI was 2.67 bales/ML compared to 1.51 bales/ML for the furrow system. This represented a 77% increase in IWUI by using SDI instead of the furrow system. The GPWUI was 1.39 bales/ML for SDI and 0.95 bales/ML for the furrow system, which represented a 46% increase in GPWUI with SDI over furrow. However, analysis should also be performed to evaluate the economic feasibility of SDI compared with furrow.

Table 5. Comparison of cotton irrigated with subsurface drip irrigation and furrow irrigation from commercial (Biloela) and demonstration (Dalby and Moree) fields (Adapted from Harris, 2005).

			Subsurface Drip					Furrow Irrigation				
Site	Grower	Year	Yield (bales/ha)	Irrigation (ML/ha)	Rain (ML/ha)	IWUI (bales/ML)	GPWUI (bales/ML)	Yield (bales/ha)	Irrigation (ML/ha)	Rain (ML/ha)	IWUI (bales/ML)	GPWUI (bales/ML)
Biloela	B	95-96	10.13	4.69	4.30	2.16	1.13	8.40	5.68	4.30	1.48	0.84
	C	95-96	8.65	2.17	4.30	3.99	1.34	8.65	5.43	4.30	1.59	0.89
	B	96-97	9.26	3.71	3.64	2.50	1.26	8.89	5.19	3.64	1.71	1.01
	B	96-97	10.32	3.71	3.64	2.78	1.40	8.89	5.19	3.64	1.71	1.01
Dalby		2000-01	10.00	4.50	3.96	2.22	1.18	7.98	5.30	3.96	1.51	0.86
		2001-02	8.78	4.20	4.40	2.09	1.02	8.20	5.60	4.40	1.46	0.82
		2002-03	10.10	2.90	6.08	3.48	1.12	9.80	5.60	6.08	1.75	0.84
Moree		2000-01	7.36	3.73	1.50	1.97	1.41	7.80	6.00	1.50	1.30	1.04
		2001-02	7.42	3.29	1.84	2.26	1.45	6.80	5.85	1.84	1.16	0.88
		2002-03	8.37	2.60	0.62	3.22	2.60	10.18	7.27	0.62	1.40	1.29
Averages:												
Biloela			9.59	3.57	3.97	2.86	1.28	8.71	5.37	3.97	1.62	0.94
Dalby			9.63	3.87	4.81	2.60	1.11	8.66	5.50	4.81	1.57	0.84
Moree			7.72	3.21	1.32	2.48	1.82	8.26	6.37	1.32	1.29	1.07
Overall Average			9.04	3.55	3.43	**2.67**	**1.39**	8.56	5.71	3.43	**1.51**	**0.95**

WUE from furrows and siphon-less irrigation systems

Hood and Carrigan (2006) compared GPWUI values from four “siphon-less” systems with adjacent furrow-irrigated fields. The four “siphon-less” systems included overhead irrigation (lateral move), “bank-less channel,” “bank-less head ditch,” and “pipes through the banks” systems. Water balance data were collected from farmers fields located throughout the Border River and Lower Balonne catchments. Results in Table 6 show higher GPWUI values for the “Pipe through the bank” and lateral move system compared with furrow, while lower values were obtained with the “Bank-less channel” and “Bank-less head ditch” systems.

Table 6. Gross production water use index (GPWUI =lint yield/total water) for cotton obtained with “siphon-less” and furrow irrigation systems. Adapted from Hood and Carrigan (2006).

“Siphon-less” system	**GPWUI (bales/ML)**	
	“Siphon-less”	**Furrow**
Bank-less Channel	1.06	1.11
Bank-less head ditch	0.45	1.06
Pipe through the bank	0.88	0.78
Lateral move	1.30	0.93
Average	**0.92**	**0.97**

WUE from alternative management of furrow irrigation systems

Vaschina (2001) compared three alternative management options for a furrow irrigation system in a field near Macalister. Results in Table 7 show an increase in IWUI from 1.50 to 1.80 bales/ML by using “single syphon/alternate furrow” instead of “single syphon/every furrow.” Since yields were the same with both management options, the increase was due to a reduction in irrigation amount from 7.00 to 5.83 ML/ha, a reduction of 1.17 ML/ha. This was a big reduction in water use, especially considering that at the time, they reported an average gross return of $800/ML (ML of irrigation) and an irrigation water savings of 1.17 ML/ha could return $936/ha. Although this was only data from one site-year, it shows the kind of management improvements that can be made at the field level to increase IWUI.

Table 7. Results from alternative management of a furrow irrigation system in a cotton field at Macalister, Australia. IE=irrigation efficiency, IWUI =irrigation water use index (lint yield/irrigation) (Vaschina, 2001).

Plot	**IE (%)**	**Yield (bales/ha)**	**Yield (kg/ha)**	**Irrigation (ML/ha)**	**IWUI (bales/ML)**	**IWUI (kg/ha/mm)**	**Gross Return ($/ML)**
Single Syphon/Alternate Furrow	78	10.50	2384	5.83	1.80	4.09	$882
Double Syphon/Alternate Furrow	64	11.00	2497	6.88	1.60	3.63	$784
Single Syphon/Every Furrow	73	10.50	2384	7.00	1.50	3.41	$735
Average	**72**	**10.67**	**2421**	**6.57**	**1.63**	**3.71**	**$800**

WUE from different row configurations

In Australia, cotton producers use different row configurations, including solid, single skip, double skip, wide row, and alternate skip. Although skip-row configurations instead of solid configurations are mainly used in dryland production, they are also being used in irrigated cotton in situations where water is limited. Results of research comparing yields of solid to single skip and double skip cotton in Australia resulted in the following equations (Gibb, 1995):

$$Yss = 0.82Ys + 0.36$$

$$Yds = 0.58\ Ys + 0.79$$

Figure 4. Cotton planted on alternate skip row configuration near Emerald.

Figure 5. Cotton planted on single skip row configuration on the Darling Downs.

Where, Yss = single skip yield, Yds = double skip yield, Ys = solid yield, all in units of bales/ha. The equations were derived from over 30 separated irrigated and dryland experiments conducted during 1984-1993 in Central Queensland and the Darling Downs.

A plot of these equations (Fig. 6) shows that Ys>Yss>Yds, except for very low yield levels (ie. Yields < 2.5 bales/ha). Similar relationships were also reported by Goyne and Hare (1999) (Fig 7).

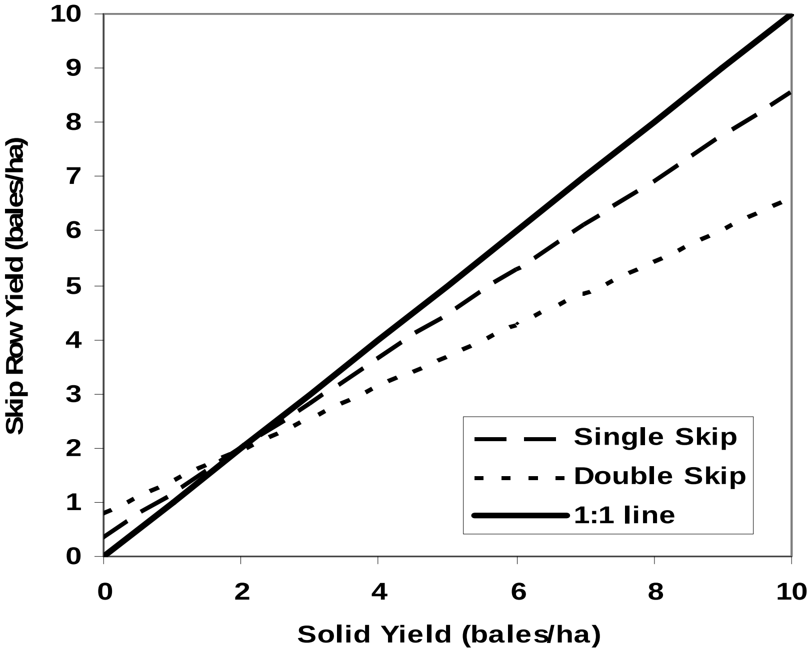

Figure 6. Relationships between cotton yields of solid row and skip row configuration (Gibb, 1995)

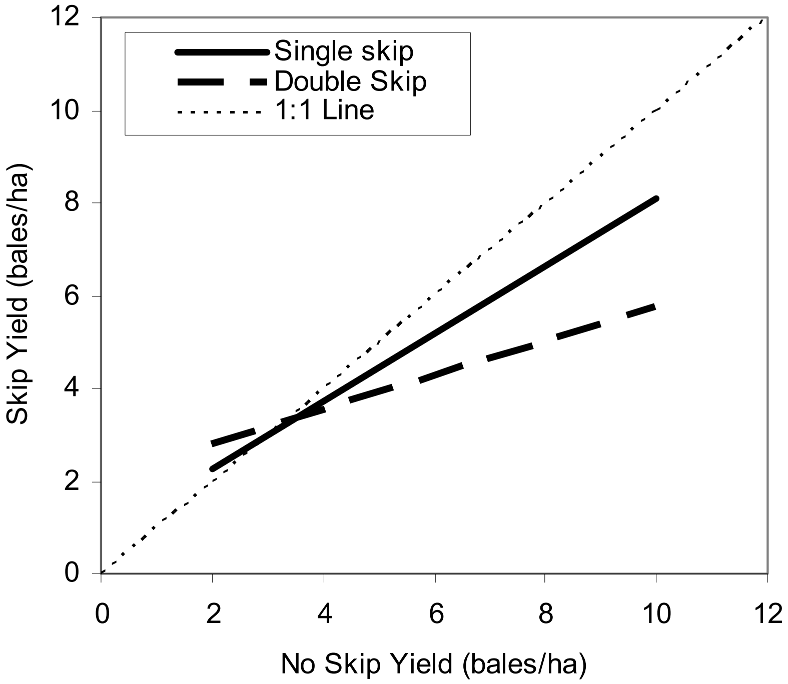

Figure 7. Relationships between cotton yields of solid row and skip row configuration reported by Goyne and Hare (1999).

The effect of row configuration on GPWUI and IWUI values are shown in Fig. 8 (Goyne and Hare, 1999) and Table 8 (Gibb, 1995). These results show that, overall, the configurations with higher yields will also tend to have higher WUE in terms of bales/ML of irrigation (IWUI) or total water (GPWUI).

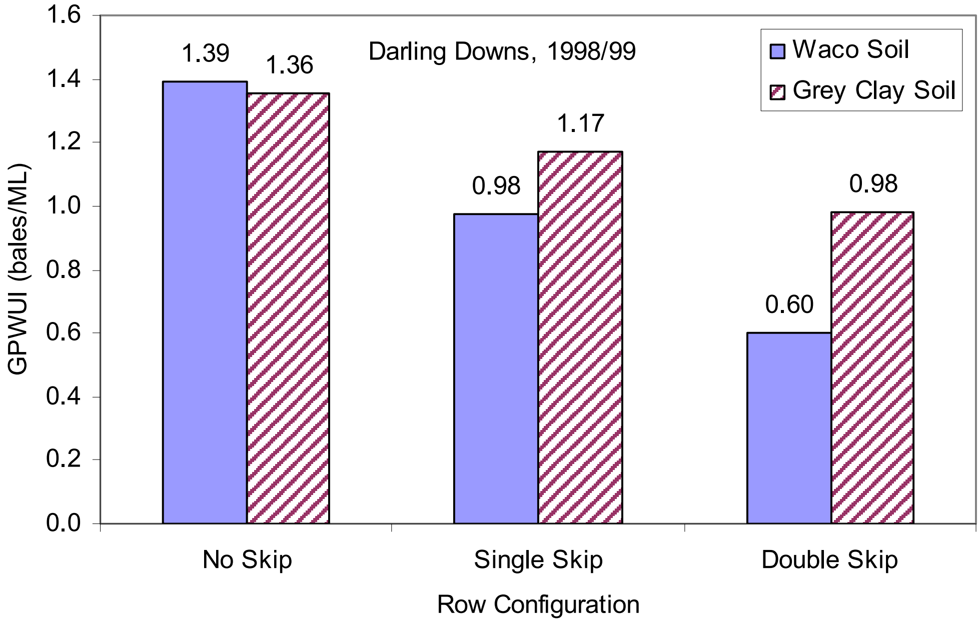

Figure 8. Gross production water use index (yield/[soil water + rain]) for dryland cotton obtained with different row configurations and two soil types (Goyne and Hare, 1999).

Although skip row configurations give up yield potential compared with solid planting when water is not severely limited, they reduce risk of crop failure when water is limited. Also, since production costs can be significantly reduced with skip row gross margins per unit area ($/ha) could actually increase with skip row compared to solid planting. Goyne and Hare (1999) reported gross margins for single and double skip rainfed cotton of $532/ha and $604/ha, respectively, compared with only $398/ha for solid planting.

Additional potential income from skip row configurations under water limiting situations can also derive from the premium price due to improved fibre quality compared with solid planting.

Table 8. Water balance and cotton water use efficiency indices obtained from several fields and row configurations during the 1994/95 season (Gibb, 1995).

Row Configuration	**Field #.**	**Irrigation**	**Rainfall**	**Total**	**Yield**	**GPWUI**	**IWUI**
		|----------------	(ML/ha)	----------------|	(bales/ha)	|------(bales/ML)	------|
Solid	105	2.87	0.80	3.67	8.60	2.34	3.00
	106	3.68	1.04	4.72	8.79	1.86	2.39
	135	4.88	0.69	5.57	8.52	1.53	1.75
	136	4.99	0.79	5.78	9.24	1.60	1.85
	137	4.77	1.03	5.80	8.67	1.49	1.82
Double Skip	131	3.24	1.84	5.08	4.59	0.90	1.42
	133	3.69	1.72	5.41	4.20	0.78	1.14
	134	3.79	2.00	5.79	4.92	0.85	1.30
Single Skip	319	2.00	0.98	2.98	2.72	0.91	1.36
	110	2.00	2.30	4.30	3.70	0.86	1.85
Averages:							
Solid		4.24	0.87	5.11	8.76	1.77	2.16
Double Skip		3.57	1.85	5.43	4.57	0.84	1.28
Single Skip		2.00	1.64	3.64	3.21	0.89	1.61

GPWUI =gross production water use index (yield/total water)
IWUI = irrigation water use index (yield/irrigation)

Irrigation efficiencies

The water component of WUE is affected by irrigation efficiency. Irrigation efficiency can be defined in many ways, depending on the scale (i.e., system, farm, and paddock scales) and purpose. In general, it is an indicator of what proportion of the water that is diverted for irrigation from a given source is actually used beneficially for the intended purpose. High irrigation efficiencies are usually desirable to reduce water waste and contribute to increase WUE. In Australia, several studies have evaluated cotton irrigation efficiencies at different scales. For example, Dalton et al. (2001) found that the whole-farm irrigation efficiencies (WFIE) (water utilized by crop/water delivered to farm) in the Australian cotton industry ranged between 21 and 65%. They also found that on-farm storage efficiency ranged from 50 to 85%, in-field application efficiency ranged from 70 to 88%, and in-field deep drainage losses ranged from 11 to 30% over the season.

Most cotton farmers in Australia previously believed that water losses by deep drainage were insignificant in the heavy clay soils in which most of the cotton is grown. They also found that water logging created by furrow irrigation in the heavy clay soils was a potential source of significant yield reduction. They even suggested that cotton yields could be increased by 20% by reducing water logging. The partitioning of the estimated water losses within the farm and the whole-farm irrigation efficiency from this study were summarised by Hood and Wigginton in Table 9. The study estimated whole-farm irrigation efficiency of only 43%, which was even lower than the values previously reported by Goyne in 2000. Surprisingly, the main water losses were due to evaporation and seepage during storage, which combined for 35% of the on-farm water losses, followed by field seepage (deep drainage) (10%).

Table 9. Water losses on Australian cotton farms (Dalton et al., 2001). Losses were calculated as a % of the water available at the farm gate.

Source	Loss (%)
Dam Evaporation	30
Dam Seepage	5
Distribution Evaporation	4
Distribution Seepage	6
Field Evaporation	2
Field Seepage	10
Total Losses	**57**
Irrigation Efficiency	**43**

They suggested that realistic potential improvements in water management in cotton could be gained by:

- Reducing evaporation from storages by 20-50%
- Reducing deep drainage by 10-15%
- Increase cotton yields by 20% by reducing water logging

Whole-farm irrigation efficiency values for each of the cotton producing areas for three seasons were also reported by Tennakoon and Milroy in 2003 (Fig. 7). Values varied considerably with season and valley. The efficiencies were higher than the average reported by Dalton et al., (2001), but still the industry average whole-farm irrigation efficiency ranged from 54 to 60%.

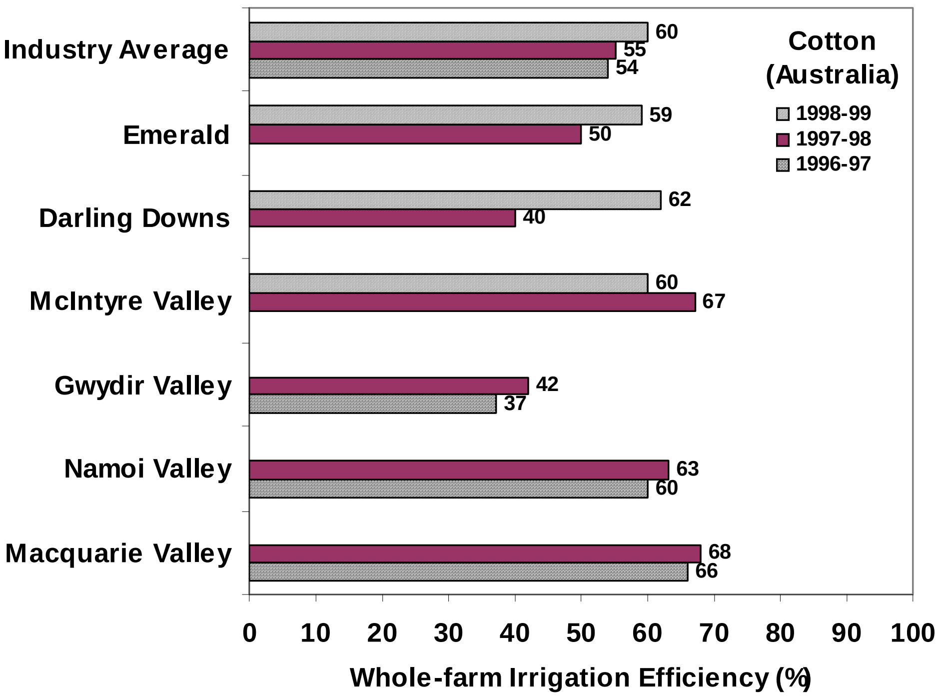

Figure 9. Whole-farm irrigation efficiencies obtained during three seasons in the different cotton producing valleys in Queensland and New South Wales. Adapted from average values reported by Tennakoon and Milroy (2003).

Smith et al. (2005) reported results of evaluation of surface irrigation events in cotton fields in Queensland. They found that at the field level:

- Irrigation application efficiencies varied widely from 17-100% with an average of 48%,
- Deep percolation losses averaged 42.5 mm per irrigation, representing an annual loss of up to 2.5 ML/ha.
- Irrigation application efficiencies in the range of 85-95% were achievable by optimising furrow irrigation in all but the most adverse conditions.

Also, reviewing available data on deep drainage in irrigated cotton in Australia, Silburn and Montgomery (2004) found that for furrow–irrigated fields, annual deep drainage rates of 1-2 ML/ha were typical, and that values ranging from 0.03 to 9 ML/ha had been observed.

In summary, the above studies suggest that about half of the water reaching the Australian cotton farms is lost during storage, conveyance, and field application, with only half available for crop use. Most water losses seem to occur during storage and conveyance, before the water reaches the field. In some areas, attempts to reduce these losses through canal lining are being undertaken. Since runoff from furrow irrigation is mostly captured and reused, water losses in the field are mostly due to deep drainage (seepage), with small losses due to evaporation from the soil surface. There seems to be potential for significantly reducing field deep drainage by optimising furrow irrigation or changing to more efficient irrigation systems.

International Cotton WUE

Data on yield and water used in different countries have been presented in the Water Footprint of Nations (Chapagain and Hoekstra, 2004), which can be used to obtain an estimate of the average IWUI for the main cotton producing countries. Cotton yields, irrigation water use, and IWUI, according to this source, for the different countries are shown in Figs 8 to 10. They show that on average for 1997 to 2001, the highest cotton yields were obtained in Israel, followed by Australia, with high variability among countries.

Irrigation water used varied widely from 4.4 ML/ha in China to 8.8 ML/ha in Iraq. The large range in irrigation water use is due to differences in crop water requirements (largely a function of differences in weather conditions among countries) and irrigation water management. The IWUI was highest for China and Israel, followed by Australia. However, the IWUI is not a good index for comparison. The CWUI would be preferable for comparison, but data are more limited.

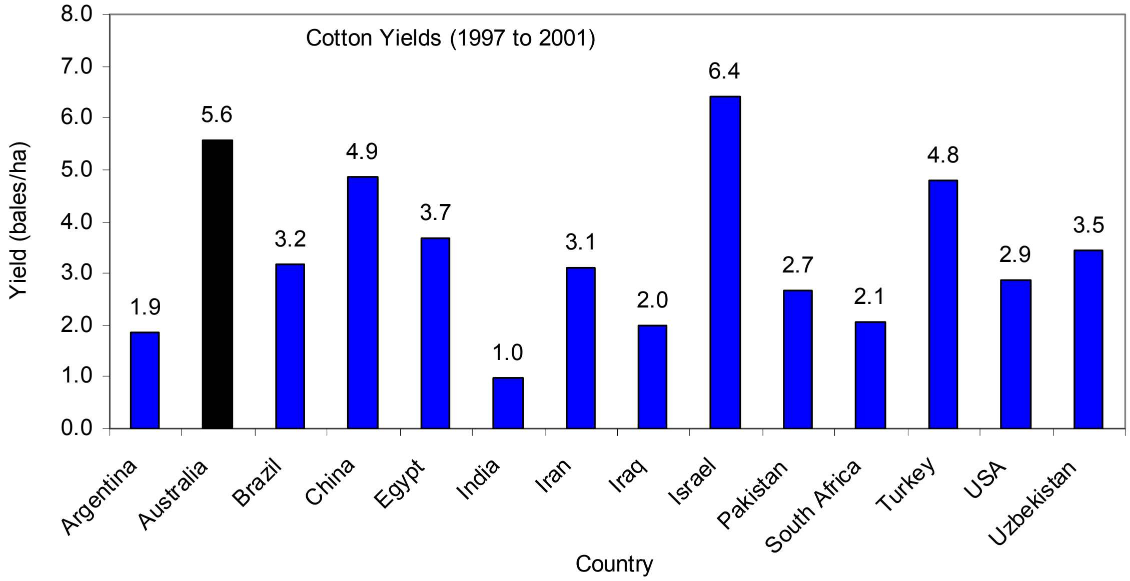

Figure 10. Cotton yields by country. Adapted from data in Chapagain and Hoekstra (2004).

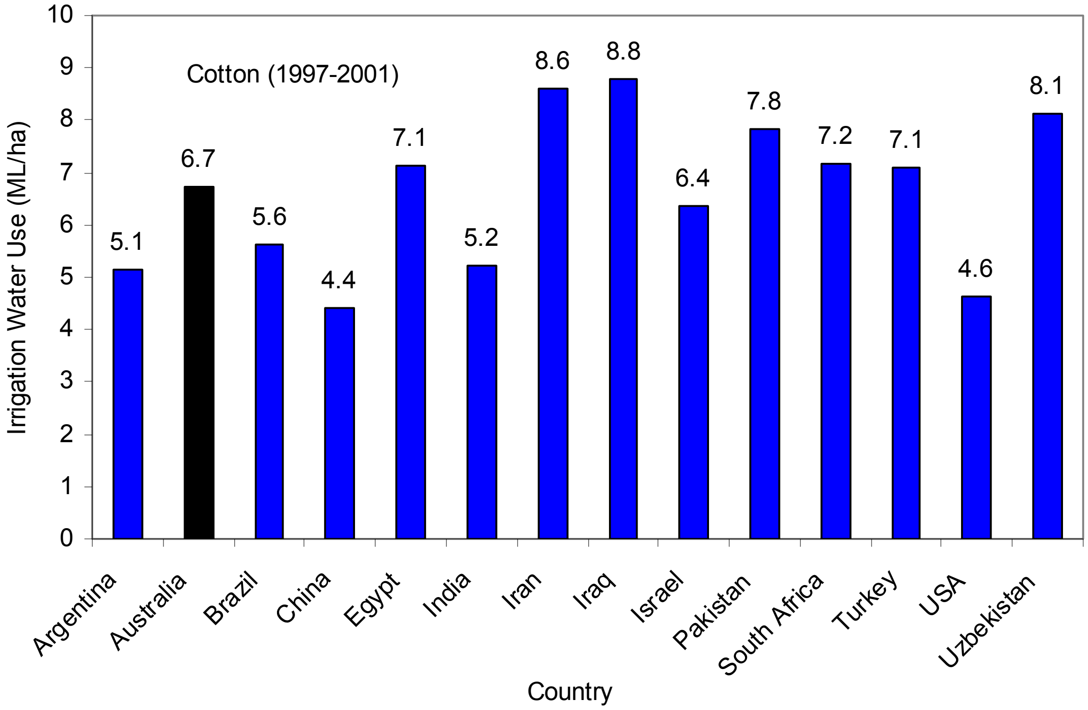

Figure 11. Cotton irrigation water use by country. Adapted from data in Chapagain and Hoekstra (2004).

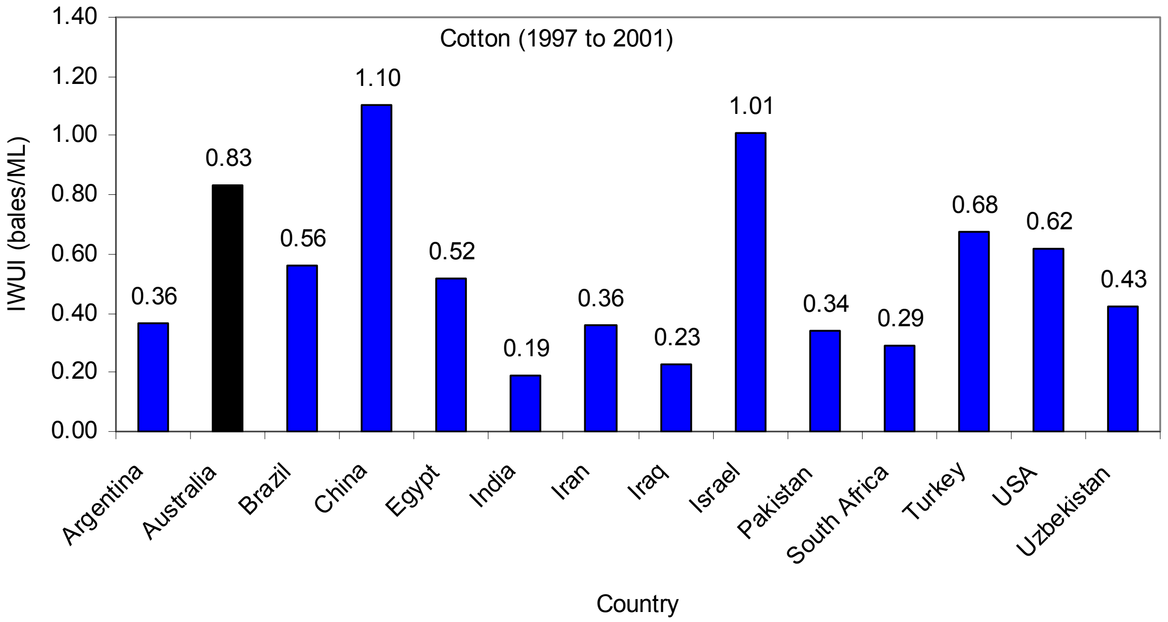

Figure 12. Cotton irrigation water use index (IWUI =lint yield/irrigation) by country. Adapted from data in Chapagain and Hoekstra (2004).

Data obtained from the AgriPartners Crop Irrigation and Production Summary, 2005 summarised the irrigation performance of cotton crops in northern Texas from 1998 to 2005. These crops were irrigated mostly with centre pivots, but data include a few entries from fields using drip and furrow systems. The data available allowed calculation of the IWUI and the GPWUI (Table 10). Average yields in this dataset have tended to increase from 1998 to 2005, but are still very low compared to the yields obtained in Australia. Yields averaged 5.0 bales/ha, which is about half of the average yields from crop competition data in Australia. Despite the low yields, both the IWUI and GPWUI values are much higher than the industry average reported by (Tennakoon and Milroy, 2003) for Australia, although they are still lower than the values from the Australian crop competition data.

Given the low yields obtained in Texas, the relatively high IWUI and GPWUI values are due to low irrigation, which averaged only 2.6 ML/ha. The low irrigation could be due to low irrigation requirements, but could also be due to the widespread use of high-efficiency irrigation systems such as centre pivots and drip systems. Also, it could be due to widespread use of deficit irrigation due to irrigation water shortages.

Table 10. Cotton water use indices obtained by farmers in Texas, USA. Adapted from data reported by New (2005). Most data were from centre pivots, but also include a few entries from drip and surface systems.

Year	Number of Entries	Irrigation (mm)	R+I+S (mm)	PET (mm)	%PET	Yield (bales/ha)	IWUI (bales/ML)	GPWUI (bales/ML)
1998	9	280	483	555	87	4.47	1.70	0.92
1999	4	240	635	553	115	4.22	2.16	0.66
2000	6	293	572	643	92	4.01	1.41	0.72
2001	13	244	493	587	86	4.04	2.26	0.83
2002	15	313	647	758	87	5.21	1.86	0.80
2003	16	294	624	723	87	5.23	2.04	0.86
2004	9	254	647	719	91	4.82	1.98	0.74
2005	17	197	568	717	80	6.24	3.55	1.09
Total	**89**	**263.43**	**583.11**	**677.54**	**87.46**	**5.00**	**2.24**	**0.86**

R= rain, I=irrigation, S = soil water depletion, PET = potential evapotranspiration, %PET = 100(R+I+S)/PET, IWUE = irrigation water use index (lint yield/irrigation, GPWUI = gross production water use index (lint yield/total water [R+I+S]).

How to improve WUE

WUE can be increased in several ways, by modifying either or both of its components ("yield" and "water"). In the past, considerable improvements in WUE have come from increasing crop yield by improving both crop varieties and agronomic practices. There is still much potential, however, to focus on the "water" part of the WUE equation. However, since CWUI increases with irrigation (as ET increases), and IWUI decreases with irrigation in areas with positive dry land yields, like in most agricultural areas, defining which of these indices the industry wants to increase is the first step towards defining the strategy to follow. Different and often opposite strategies need to be used to increase the CWUI, IWUI, or economic returns:

How to increase CWUI

- Increasing crop yields by developing varieties with higher yield potential, and improving agronomic practices.
- Increasing crop yield by minimising crop water stress and increasing transpiration by:
  - If water is not limited, fully-irrigating to meet crop water requirements
  - If water is limited and deficit irrigation is required:
    - If possible, timing irrigations to minimise stress during high ET periods.
    - Reducing irrigated area to better meet crop water requirements instead of deficit-irrigating a larger area.
- Increasing yields by controlling yield limiting factors like insects, weeds, diseases, crop nutrition, soil salinity, water logging, etc
- Reducing evaporation water losses, which can be achieved by:
  - Avoiding irrigating more frequently than necessary to meet crop water needs.
  - When possible, avoiding irrigation during the early stage of the crop when canopy cover is low and evaporation is high compared with transpiration. This strategy, however, needs to be used with caution, since delaying irrigation can create crop stress and significantly reduce yields.
  - Using mulching by crop residue or other feasible means.
  - Minimizing unnecessary tillage that exposes stored soil water to evaporation.
  - Using irrigation systems and management strategies that minimise evaporation (such as subsurface drip irrigation, and irrigating alternate furrows instead of every furrow when using furrow irrigation).
  - Using the highest plant density that best management agronomic practices and water availability allow.

How to increase IWUI

- Increasing yield using the strategies listed above that does not require additional irrigation.
- At the field level, decreasing irrigation by:
  - Deficit-irrigating a larger area instead of fully-irrigating a smaller area.
  - Increasing irrigation efficiency
    - Using more efficient irrigation systems (drip, sprinkler, optimised furrow)
    - Decreasing irrigation requirements by capturing more rain and reducing evaporation (reduced tillage, residue management, land levelling, terracing, crop rotation, proper sowing time…)

    - Improving irrigation scheduling and management
        - Applying the right amount of irrigation at the right time.
        - Optimising the irrigation system to improve irrigation uniformity and reduce water losses (gated pipes, surge flow, alternate furrows…).
        - Recycling water
- At the whole-farm level, decreasing water losses during storage and distribution.

How to increase economic returns

Unlike the IWUI, the increasing trend in CWUI with ET does not depend on the sign of the dry land yield. Therefore, for areas and seasons with a positive dry land yield, the CWUI will tend to increase with irrigation while the IWUI will tend to decrease. Since the two indices have opposite behaviour with irrigation, the question then is which of the two indices the industry should try and increase. The answer to this question will probably be the strategy that maximizes profits without wasting water.

A recent study from India (Kar et al., 2007) showed that increases in ET due to irrigation also increased CWUI and profitability per unit area for three crops (linseed, safflower, and mustard). Similar increasing returns per unit area ($/ha) with increasing crop water use for wheat, barley, and canola was reported in Australia (Montagu et al., 2006). This means that profitability per unit area ($/ha) increased with CWUI and decreased with increasing IWUI. It should be kept in mind that the CWUI can be maximised by over-irrigating. Over-irrigation will waste water and will not produce additional yield, in fact, it can reduce yields. Therefore, if the objective is to maximise CWUI, care should be taken to increase it without over-irrigating.

The study in India, however, only analysed the profitability per unit area ($/ha), which would be appropriate in situations where area is the factor limiting production. However, in other situations other factors like water, capital, labour, etc, can be limiting. In Australia, land is abundant and water is usually the limiting factor. In this situation, water saved by deficit-irrigation could potentially be used to increase the area planted. Therefore, it is imperative to consider not the profit per unit area ($/ha), but the profit per unit of irrigation ($/ML), and even more importantly, to identify the water management or water allocation option that will maximize profits of the whole farming enterprise ($/farm).

Objective 2

2.1 Re-survey of Tennakoon WUE Survey

2.1.1 Tennakoon WUE Survey in the 1990's

As part of the project it was deemed timely to re-visit and determine the current status of water use efficiency of those irrigation farms surveyed and reported on by Tennakoon (2000). It could then be determined if changes have occurred since the original survey.

Sunnil Tennakoon collected around 200 individual sets of historical water management field data (from the seasons 1993 to 1998) from 25 cotton farms in the cotton growing regions of the Namoi Valley, Gwydir Valley, Macquarie valley, McIntyre Valley, Darling Downs and Emerald. The field level data collected (for 3 to 4 fields per season for each farm) included:

- Neutron probe soil moisture readings
- Date of sowing and harvesting
- Dates of irrigation
- Lint yield
- Previous crop and soil type

The farm level data collected included:

- On farm daily rainfall
- Total cotton area
- Total water pumped (for cotton) from the river (ML)
- Total water pumped (for cotton) from bores (ML)
- Total on farm harvested water and stored water usage (ML)

In addition to on farm daily rainfall, the climatic data for the estimation of evapotranspiration was obtained from the meteorological stations nearest the farms.

Tennakoon used a desktop methodology to assess the water use efficiency of the surveyed farms and hence that of the cotton industry. He calculated seasonal water use and water use efficiency. A requirement for doing this was the estimation of seasonal evapotranspiration (ET) using the volumetric soil moisture in the soil profile, determined from the neutron probe data. However, because of the irregularity in the taking of neutron probe readings it was necessary for Tennakoon to develop a daily water balance model to fill in the gaps in the neutron probe data. He was then able to estimate daily ET, net irrigation intakes and effective rainfall in the irrigated cotton crops.

Tennakoon and Milroy (2003) subsequently published the results of the survey and concluded that, as there was a wide variation in both crop water use efficiency and irrigation efficiency, significant potential exists for some producers to increase their efficiencies.

2.1.2 Re-survey Methodology

Following the original surveys Tennakoon, Johnson, and Milroy (2001), developed the Water Use Efficiency Calculator (WUE Calculator) software tool as an extension of the procedures used by Tennakoon (2000). This software provides for the recording and analysis of water management data to assess the performance of individual fields and whole farm water use efficiencies using a minimum set of measurements similar to those used by Tennakoon (2000). For the re-survey of the farms that participated in the original survey it was decided to use the WUE Calculator to process data collected. However, a valid comparison between the original efficiencies and current efficiencies could only be made if the WUE Calculator provided similar output to that of Tennakoon's methodology.

A random selection of over 50 sets of Tennakoon's original data was therefore processed through the WUE Calculator. Table 1 shows the percentage difference between Tennakoon's calculations and those determined by the WUE Calculator.

Table 1 Percentage differences in WUE Indices between the WUE Calculator and the original Tennakoon methodology

Valley	Farm	Crop WUE (kg/ha/mm)	Gross Water Use Index (bales/ML)	Irrigation Water Use index (bales/ML)
Namoi	Merinda	0.5%	0.0%	-4.4%
Namoi	Beechworth	2.2%	1.9%	1.9%
Namoi	Beechworth	2.1%	1.3%	1.9%
Namoi	Beechworth	2.0%	1.3%	2.3%
Namoi	Beechworth	3.3%	3.0%	4.2%
Namoi	Beechworth	2.1%	2.0%	1.8%
Namoi	Beechworth	1.9%	1.4%	2.1%
Namoi	Beechworth	5.7%	5.8%	6.1%
Namoi	Beechworth	2.2%	1.6%	1.9%
Namoi	Beechworth	2.3%	2.4%	2.3%
Namoi	Waverley	-3.7%	-4.5%	-0.6%
Namoi	Togo	-0.8%	-1.3%	0.7%
Namoi	Togo	0.0%	-0.3%	-1.2%
Namoi	Togo	0.1%	-0.1%	0.7%
Namoi	Togo	1.3%	0.3%	0.5%
Namoi	Togo	0.4%	-0.4%	0.7%
Gwydir	Bellevue	-7.4%	-8.0%	-9.7%
Gwydir	Bellevue	-3.4%	-4.0%	-3.9%
Gwydir	Bellevue	-1.5%	-1.6%	-0.8%
Gwydir	Bellevue	-2.5%	-3.0%	1.3%
Gwydir	Bellevue	2.8%	1.9%	10.0%
Gwydir	Iffley	61.7%	60.7%	41.8%
Gwydir	Iffley	-2.3%	-2.4%	-2.3%
Gwydir	Iffley	-3.5%	-3.7%	-2.3%
Gwydir	Iffley	-2.9%	-3.3%	-2.9%
Gwydir	Iffley	-2.4%	-3.0%	-2.0%
Gwydir	Moonim	1.5%	0.8%	-1.9%
Gwydir	Moonim	5.7%	5.6%	12.5%
Gywdir	Telleraga	-12.8%	-13.3%	-12.0%
Gywdir	Telleraga	-5.7%	-6.3%	1.3%
Gywdir	Telleraga	-3.6%	-4.5%	0.6%
Gywdir	Telleraga	-5.6%	-6.4%	0.3%
Gywdir	Telleraga	-8.7%	-8.9%	0.0%
Gywdir	Telleraga	5.3%	5.2%	22.8%
Gywdir	Telleraga	-12.5%	-12.7%	0.0%
Gywdir	Telleraga	3.9%	3.7%	20.9%
Gywdir	Telleraga	2.0%	1.2%	18.4%
Gywdir	Telleraga	-6.1%	-6.6%	0.7%
Gywdir	Telleraga	1.7%	1.2%	3.1%
Gywdir	Telleraga	1.4%	1.4%	2.0%
Gywdir	Telleraga	21.6%	20.6%	55.1%
Gywdir	Telleraga	-21.6%	-21.9%	20.8%
Gywdir	Telleraga	0.6%	0.6%	0.6%
Gywdir	Telleraga	15.6%	15.1%	52.6%
Macquarie	Auscot	-2.0%	-2.3%	-4.0%
Macquarie	Auscot	-1.2%	-1.7%	0.0%
Macquarie	Auscot	-3.1%	-3.5%	-5.1%
Macquarie	Auscot	-2.2%	-2.7%	-2.9%
Macquarie	Auscot	-3.3%	-3.4%	-4.1%
Macquarie	Auscot	-3.7%	-4.1%	-4.2%
Macquarie	Auscot	1.2%	0.7%	2.6%
Macquarie	Auscot	-2.4%	-3.1%	-2.1%
Downs	Wamara	-4.2%	-4.8%	-5.5%
Downs	Wamara	-4.0%	-4.1%	-6.0%

Downs	Bungaree	-4.7%	-5.7%	-6.9%
Downs	Kantara	-5.3%	-5.9%	-0.4%
Downs	Kantara	-3.8%	-4.6%	-7.6%

Table 1 shows considerable variation in the differences between Tennakoon's output and that calculated via the WUE Calculator for the three WUE indices. This indicated a need to process Tennakoon's data through the WUE Calculator and these results compared with the re-survey data output to ascertain if changes have occurred in efficiencies since the 1990's.

2.1.3 Re-Survey Data

Through the cooperation of Cotton Catchment Communities CRC Extension team and cotton growers, an attempt was made to collect data for the years 2004 to 2007 from farms which were originally surveyed by Tennakoon (2000). Appendix 2 is an example of the re-survey data collection forms used with irrigators. In addition to on farm rainfall, meteorological data were collected from the nearest weather station if there was no farm data available.

Problems were immediately encountered:

- A number of farms had changed ownership since Tennakoon's survey.
- Original owner's records not available.
- Some growers not interested in providing information.
- Farm fields were altered losing the identity of the original fields.
- Dates of planting and harvest not available from all farms.
- Monthly or weekly rainfall provided rather than daily.
- Large gaps in daily meteorological data.
- Dates irrigation water applied not available in some cases.
- No farms were available with a complete set of required data to enable satisfactory processing via the software tool.

Numerous attempts were made to repair the gaps in meteorological data by obtaining data from the Meteorological Bureau and from other available data sets. However, none of these attempts were satisfactory. A major omission from the data sets and a necessary parameter to run the software tool was wet bulb temperatures. This appears to be unattainable for most of the historical data sets.

2.1.4 Conclusions

The difficulty in obtaining sufficient and adequate data from the original 25 farms surveyed by Tennakoon has meant that the re-survey had to be abandoned. A more useful approach to obtain this data in the future would be annual collection of datasets using WaterTrack Rapid. This could be undertaken in one of two ways:

1. An annual survey undertaken in a similar way to that by David Williams for the 2006-07 season (and reported in Williams and Montgomery, 2008).
2. An annual survey conducted by agronomic consultants with their growers in each valley

These surveys would have to be funded by industry in an ongoing fashion. The advantage of the second option is a larger dataset and involvement of consultants in the process would aid in the more widespread adoption of WUE benchmarking within the cotton industry.

2.2 Surface Irrigation Evaluations Database

2.2.1 Background

Although there have been a large number of surface irrigation evaluations performed, it is generally difficult to source reliable information on the current state of the irrigation industry. Since its commercial début in 2001, Irrimate™ has been highly successful; both considering the number of evaluations and the impressive documentable improvements in efficiency. However, the data recording and reporting processes have been managed with different levels of rigour, resulting in large volumes of information with little consistency between individuals or organisations. Consequently it is almost impossible to use this data to conduct industry wide benchmarking of existing performance and demonstrate realised and potential improvements to irrigation performance.

2.2.2 ISID – Irrimate Surface Irrigation Database

The Irrimate Surface Irrigation Database, known by the acronym ISID was conceived in an attempt to address these issues. Firstly it provides a standard for data recording procedures, including but not restricted to all data required for normal system evaluation. Secondly, and more importantly, ISID is a web-interfaced database which has the capacity to store large numbers of events in a hierarchical organised fashion. It is developed around a secure and proven database structure, ensuring complete anonymity of data between separate users. The complete system allows users to search through all entered evaluations to capture industry snapshots filtered by district, season, soil type and other selected parameters. ISID is designed to collate field measurements and simulation results to facilitate benchmarking of surface irrigation performance at the farm, catchment and industry levels.

The project engaged The National Centre for Engineering in Agriculture to develop ISID. A report on the development of ISID is attached as Appendix 3 - Gillies, M.H, (2008). Benchmarking Water Management in the Australian Cotton Industry. National Centre for Engineering in Agriculture Publication 1002691/2, USQ, Toowoomba.

2.2.3 Accessing ISID

ISIS is accessed through the World Wide Web using any of the popular web browsers such as Microsoft Internet Explorer, Mozilla Firefox or Netscape Navigator. Currently ISID is located on the National Centre for Engineering in Agriculture web server at http://139.86.208.170/isid.

Registered users are able to access datasets for their individual clients but cannot view datasets for other clients whose data may be in ISID. There is also an overview user login which enables anyone to view a summary of the available datasets – an overview user cannot access individual datasets. To access the overview mode the login is “overview” and the password is “overuser”.

Documentation for the use of ISID is contained in Gillies, M.H. & Curran, N (2008). ISID Irrimate Surface Irrigation Database - User Manual and Technical Documentation. National Centre for Engineering in Agriculture Publication 1002691/1, USQ, Toowoomba (see Appendix 4).

2.2.4 ISID Results

Tables 1 and 2 are a summary of the evaluation results for the 89 Irrimate evaluations currently in the ISID (this is for evaluations up to June 2006).

Table 1 Summary results of 89 Irrimate evaluations within the Cotton Industry

Measured	Average	Minimum	Maximum	Standard Deviation	Median	1st Quartile	3rd Quartile
Depth Applied (mm)	123.9	41.8	333.0	56.4	108.6	83.6	141.2
Infiltration (mm)	96.7	28.2	280.9	42.0	86.6	67.1	112.2
Deep Drainage (mm)	22.3	-0.1	223.3	31.0	13.4	1.0	30.9
Runoff (mm)	27.1	0.0	187.3	32.9	15.2	6.9	30.6
Application Efficiency (%)	64.9	17.1	97.7	17.0	67.0	54.5	77.4
Requirement Efficiency (%)	93.4	49.5	100.0	12.0	99.5	93.6	100.0
Distribution Uniformity	88.0	13.6	99.1	11.4	90.2	84.9	95.1

Table 2 Summary results following optimisation of 89 Irrimate evaluations using SIRMOD

Optimised Simulation Results	Average	Minimum	Maximum	Standard Deviation	Median	1st Quartile	3rd Quartile
Depth Applied (mm)	121.2	110.2	156.6	17.5	112.3	111.5	112.7
Infiltration (mm)	109.6	90.6	150.1	18.8	105.7	101.9	106.9
Deep Drainage (mm)	20.7	2.3	91.9	31.6	10.7	6.7	11.1
Runoff (mm)	11.8	2.3	42.3	13.6	7.7	6.2	8.5
Application Efficiency (%)	75.3	36.4	85.8	18.5	84.4	66.4	84.7
Requirement Efficiency (%)	96.0	94.6	100.0	2.1	95.0	94.8	95.1
Distribution Uniformity	79.4	73.7	91.7	5.8	77.5	76.7	79.0

The data in Table 1 shows a large range in the performance of surface irrigation within the industry. Table 2 shows the potential for improvements in the performance of surface irrigation within the industry.

2.2.5 Recommendations

For ISID to perform to its full potential the following recommendations need to be addressed.

1. **Data Entry**- ISID provides an efficient platform for data collation and storage but relies entirely on individual users entering large numbers of irrigation evaluations. The current version of ISID does not offer any significant advantage for the standard field evaluation. Instead the real value of the system is to provide benchmarks across multiple properties and irrigation districts. It is likely that implementation of some of the proposed changes outlined in Appendix 3 will provide functionality over and above the existing Irrimate procedures and hence serve as a catalyst for use of ISID. Until this occurs the data entry process will remain reliant on the diligence of users to upload and update the necessary information.

   It is perceived that the entry of past irrigation data and that of future evaluations will require funding to support a person to enter the required data. The NCEA is independent of all consultants and government agencies and hence is ideally positioned as the provider of this service. It is also important to note that all Irrimate consultants are contractually obliged to provide irrigation data to the NCEA.

2. **Data Quality Control -** Like all computer based systems, ISID is subject to the garbage in garbage out principle. The quality of the results and summary statistics is dependent on the quality of all data supplied to the system. Currently ISID does not contain any quality control measures apart from excluding those furrows with missing or incomplete information.

   Each user has complete control over the evaluations they have entered is responsible for ensuring the accuracy of all included information. The system administrator, while having control over user accounts does not have access to the entered evaluations. These measures ensure complete data confidentiality but may cause problems when data quality becomes an issue.

Data quality control issues can be addressed by one or a combination of:

1) Providing training to ensure that users are proficient in use of the system.

2) Permitting access of an administrator or data supervisors to the data to identify and fix any problems.

The required administrative workload would be greatly diminished where all users are sufficiently trained. As an alternative to the single administrator model this data checking role could be designated to a “supervisor” within each organisation. The supervisor would have access to a group of general users which would become their responsibility.

3. **Revision of the Soil Classification Information provided in SOILpak** The document: “SOILpak for cotton growers” (McKenzie 1998) provides a practical and comprehensive description of the soils most commonly found in the cotton growing regions of Australia. Unfortunately SOILpak focuses primarily on the Great Soil Group classification scheme which is not ideally suited to Australian conditions and is being superseded by the Australian Soil Classification (Isbell 1996). The Australian Soil Classification (ASC) promises to rectify the issues of the existing schemes and is uniquely designed for Australian conditions based on a database of over 14000 soil profiles across all states (Isbell 1996). The original database is slightly biased towards Queensland and focuses primarily on agricultural soils, one common criticism of the scheme but no issue for use within ISID or SOILpak.

   The ASC is a hierarchical system with mutually exclusive classes based on soil attributes relevant to land use management and applicable across all soils found within Australia. Classification is based on the physical and chemical properties of soil horizons rather than being determined by geographical position or parent materials (Isbell et al. 1997). Soils are assigned names using a classification key which has the major strength of the possibility of indentifying a new unknown soil through a logical process of elimination.

   Material is provided within the ISID user manual to help users identify the appropriate ASC soil order and sub-order for a given soil type. An abbreviated soil key can be accessed directly from the edit evaluation page by clicking the appropriate link next to the soil type information. Also found in the user manual is a table demonstrating how the soils from alternative schemes relate to the ASC, including the nomenclature used within SOILpak.

   It is strongly suggested that Part E of SOILpak for cotton growers, more specifically Chapter E1 – “*Australian Cotton Soil*” should be modified and updated to properly describe cotton growing soils in terms of the Australian Soil Classification. The same comment may also apply to the SOILpak series available for other cropping industries (e.g. SOILpak for vegetable growers, SOILpak for the northern wheat belt).

4. **Optimisation of the Data Entry Interface -** The web page interface fulfils all requirements for entry of field data but could be improved to increase loading speed, efficiency and improve readability. The inflow and runoff hydrographs are one prime example. They consist of large number of automatically uploaded data elements which require considerable room on the page and are responsible for significant loading delays. A re-design of the page would include hiding such data and re-organising the important information to decrease the page size.

   It is envisaged that several areas for improvement will be identified when ISID is released to a wider audience of users, requiring some minor changes to the system. It is envisaged that the improved interface design would be implemented during this time.

5. **Expansion to Other Industries -** ISID has been developed for the Australian cotton industry and is therefore has been designed to represent the management practices (e.g. siphon type inflow) and irrigation districts where cotton is grown. Despite this, the database itself was designed to be generic and hence can be applied across any industry where furrow irrigation is practiced. Users can currently specify crops other than cotton using the “crop” dropdown in the “Season and Irrigation History” section but cannot add additional irrigation districts. The list of soil types was devised in an attempt to represent all Australian soils of agricultural importance but additional orders or sub-

orders can be added with little effort. As a result, ISID is adaptable to any furrow-irrigated crop with minimal additional work.

2.3 HydroLOGIC Users Survey

In early 2007 a telephone survey of HydroLOGIC users was conducted by Cotton CRC staff to ascertain the extent of its use and identify any users with useful WUE data. The questionnaire used is provided in Appendix 5.

At the time of the survey there were 231 registered users of HydroLOGIC – 56% growers, 33% consultants and 10% unknown. Details of the registered users is summarised in Table 2.

The survey found that less than 10 registered users had used HydroLOGIC sufficiently to provide adequate benchmark data for use by the industry.

Table 2 Details of number of registered HydroLOGIC users at December 2006

Valley	Growers	Consultants	Unknown
Bourke	2	6	
Burnett	1	2	1
Darling Downs	20	16	5
Dawson-Callide	7		
Emerald	8	5	1
Gwydir	17	11	4
Lower Namoi	16	7	6
Macintyre	15	9	3
Macquarie	10	5	1
Southern	8	4	1
St George	8	9	
Upper Namoi	14	3	1
Walgett	4		1
Total	130	77	24

2.4 Irrigation Best Management Practice Case Studies

A summary of the number of growers accessing Rural Water Use Efficiency Incentive Funds and what these funds were spent on is provided in Table 3. On the basis of this detail it was decided not to prepare case studies on irrigation best management practice for these growers. Instead case studies were prepared by Rural Water Use Efficiency and Advancing Water Management in NSW Project staff through the Water Matters section within the Australian Cottongrower and on the Cotton and Grains Irrigation website.

Table 3 Numbers of cotton irrigators accessing Rural Water Use Efficiency Financial Incentive Scheme funding during 2001-02 and 2002-03

District	Scheduling Equipment	System Improvement	Water Meter	Weather Station	Total
Border Rivers	5	3	2	2	12
Burnett	1	0	0	0	1
Darling Downs	16	71	20	0	107
Dawson-Callide	4	13	8	1	26
Dirranbandi	2	2	11	1	16
Emerald/Mackenzie	31	21	4	14	70
Richmond	1	0	0	0	1
St George	10	4	3	0	17
Warrego	0	1	0	0	1
Total	70	115	48	18	251

2.5 Cotton BMP water management datasets

No useful irrigation management datasets were identified through the Cotton BMP PCA process conducted by Cotton Australia GSMs. In response it was decided to develop a on-line benchmarking tool that could be used by irrigators to standardise the collation of irrigation benchmarks.

Dan Hickey, formerly the Cotton Australia GSM on the Darling Downs developed the Water Benchmarking Tool with consultation with David Wigginton, formerly NSW DPI and Graham Harris, DPI&F as part of this project (and with funding by CRDC). Subsequently the tool has been incorporated into the Benchmarking module within the Cotton-Grains Irrigation Training series being delivered throughout the Cotton Industry. The tool can be accessed through the Cotton Catchment Communities CRC website and the Cotton-Grains Irrigation website, or by using the address www.morganruraltech.com.au/cottnbmp/waterHome.aspx .

Analysis of the use of the tool reveals that between 25 October 2007 and 5 November 2008 it was accessed on 94 occasions by 35 different users. Only three users agreed to make their data available to the industry.

Following release of the tool Aquatech Consulting developed WaterTrack Rapid which is a much more comprehensive tool for the benchmarking of water use at the whole farm scale. WaterTrack Rapid is a more robust tool than the Water Benchmarking Tool and could be used by the cotton industry to collect WUE Benchmarking data annually so that an accurate picture of WUE within the industry can be collated over time. In 2007-08 David Williams collected WUE benchmark data from 37 irrigators across the industry using WaterTrack Rapid – the results were presented at the Australian Cotton Conference in 2008 (Williams and Montgomery, 2008).

The data from 36 farms shows a wide range in irrigation performance across the industry. Water losses on farm range from -1.43 ML/ha to 4.71 ML/ha, with an average loss (from the 30 farms with positive losses only) of around 1.53 ML/ha. This was around 15 percent of all water used on farm for the crop. Therefore on average, the farms were able to utilise around 85 percent of their water through the plant productively. In this survey, the 6 farms with the highest combined farm water losses were only averaging around 65 percent of their total water through the crop in a productive manner. Given that there has been an underestimation of water volumes on some farms, these figures could be on the high side, however, to what extent has not been determined during this survey. The average GPWUI was 1.13 bales/ML, ranging between 0.82 and 1.71 bales/ML.

2.6 Crop Competition Datasets

To estimate cotton WUE from actual farmer's fields, data from crop competitions on the Darling Downs, which include some entries from the Lockyer Valley, were obtained. These competitions are sponsored by the Royal Agricultural Society of Queensland (RASQ) and the Darling Downs Cotton Growers Inc. This dataset has the advantage that it includes a period of 19 years (1987 to 2005) which could provide information about seasonal tendencies. On the other hand, it has the disadvantage that the information was supplied by farmers by filling up a form, which makes it difficult to ascertain data quality. Therefore, it is expected that some of the information provided by farmers was actually measured while other was just estimated. Also, since data were supplied as part of a yield competition, only farmers obtaining the best yields would have entered the competition. Data, therefore, are not expected to be representative of average farmers, but represent the best farmers in the area. As such, they provide an indication of what is actually possible for normal commercial operations in the area.

For analysis, only entries with complete records were used. An entry was considered complete if it provided information on yield, irrigation amount or number of irrigations, and in-crop rainfall. In cases where only the number of irrigation was provided, the amount of irrigation was estimated by assuming that each irrigation was equal to 1 ML/ha (100 mm), which is a common estimate used by surface-irrigators in the area (Goyne et al., 2000). The number of complete entries included in the analysis varied considerably from year to year (Figure 1). A total of 204 complete entries were analysed, including 23 dryland and 181 irrigated entries. Dryland entries for cotton are only available since 2000.

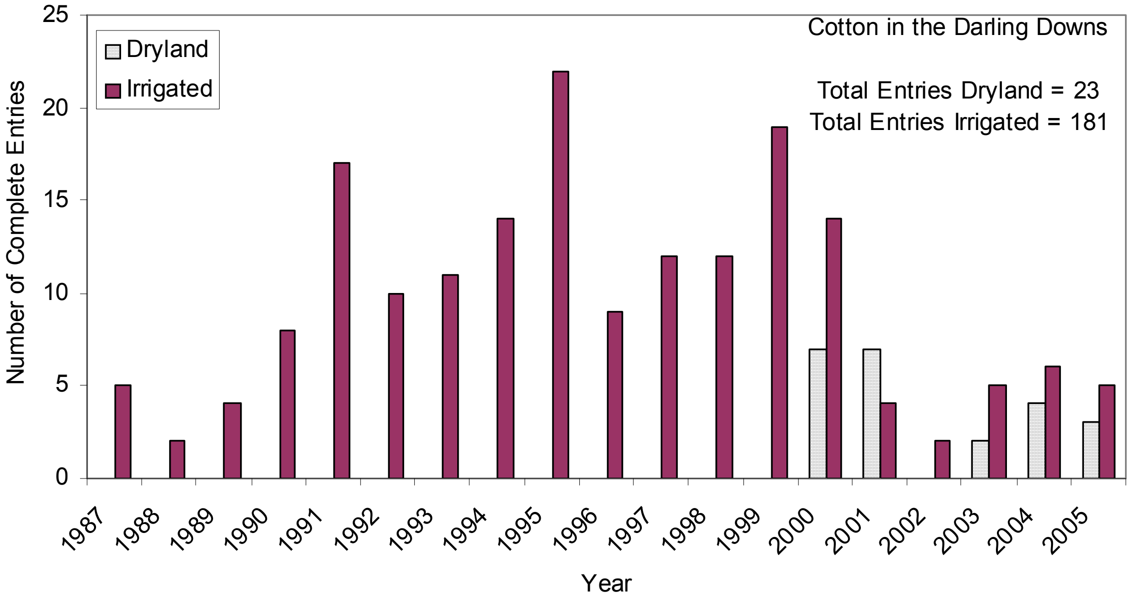

Figure 1 Number of complete entries for farmers participating in cotton yield competitions in the Darling Downs, Australia. An entry was considered complete if it provided information on yield, number of irrigations, and in-crop rain.

Results indicate that irrigation amounts, dryland yields, and WUE indices were affected by in-crop rainfall. The average in-crop rainfall reported by farmers during the 1987-2005 period was 4.23 ML/ha (423 mm), with significant variability from year to year, ranging from approximately 250 mm in 1993, 1997, 2003, and 2005 to more than 650 mm in 1996 (Figure 2).

Irrigation amounts and number of irrigations varied considerably from year to year (Figures 3 and 4). On average, farmers reported applying 3.4 irrigations (including pre-irrigation), representing an average of approximately 3.5 ML/ha. Figure 3 shows that although the number of irrigations tended to decrease with in-crop rainfall, the relationship had several outliers that suggest the influence of other factors, such as lack of water to satisfy crop water demands, inappropriate irrigation scheduling, occurrence of sudden storms that farmers could not anticipate, etc.

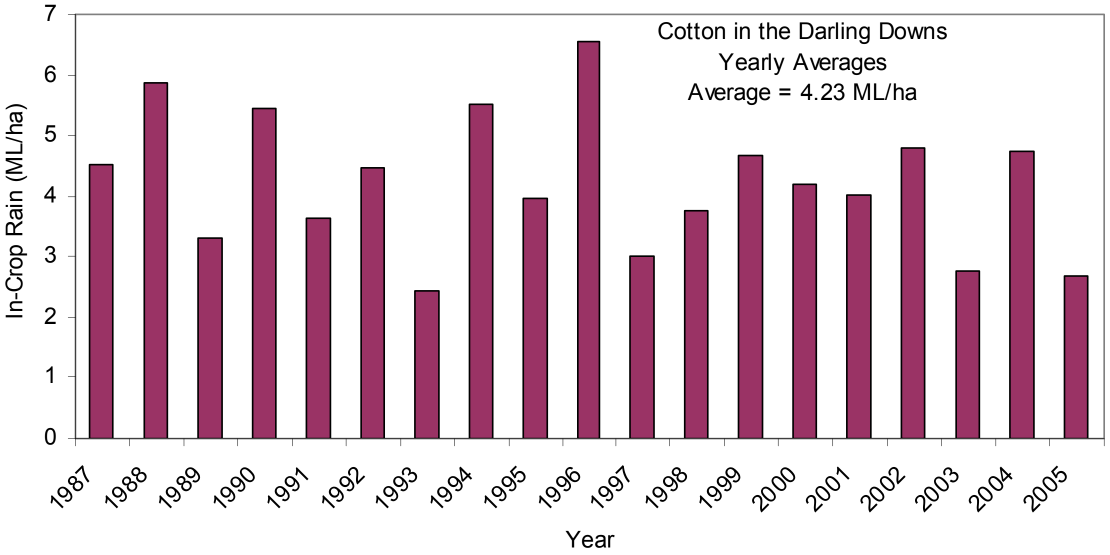

Figure 2. Average in-crop rain for cotton by year, reported by farmers participating in yield competitions in the Darling Downs, Australia.

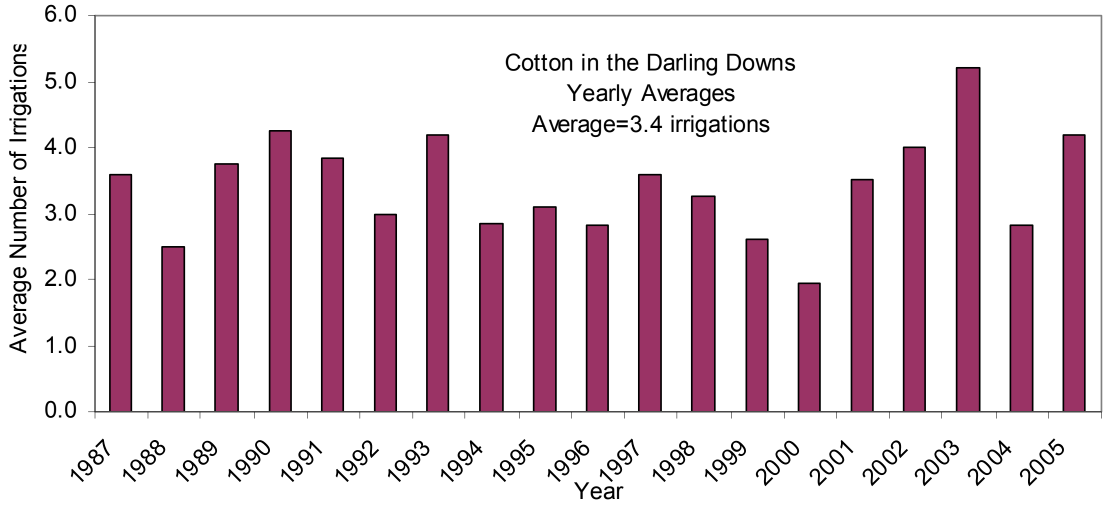

Figure 3. Average number of irrigations for cotton by year, applied by farmers participating in yield competitions in the Darling Downs, Australia.

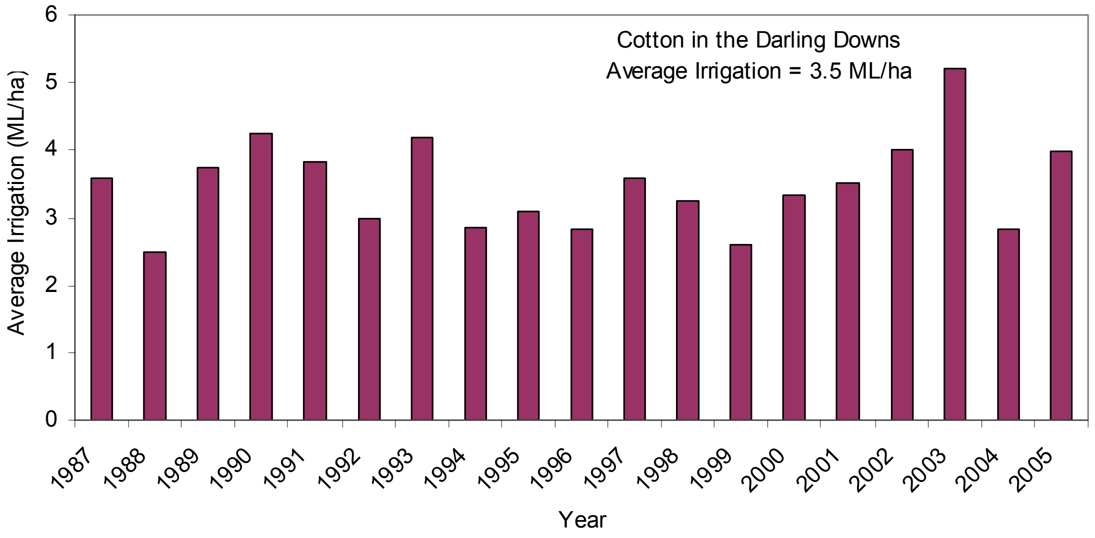

Figure 4. Average irrigation amount for cotton by year, reported by farmers participating in yield competitions in the Darling Downs, Australia.

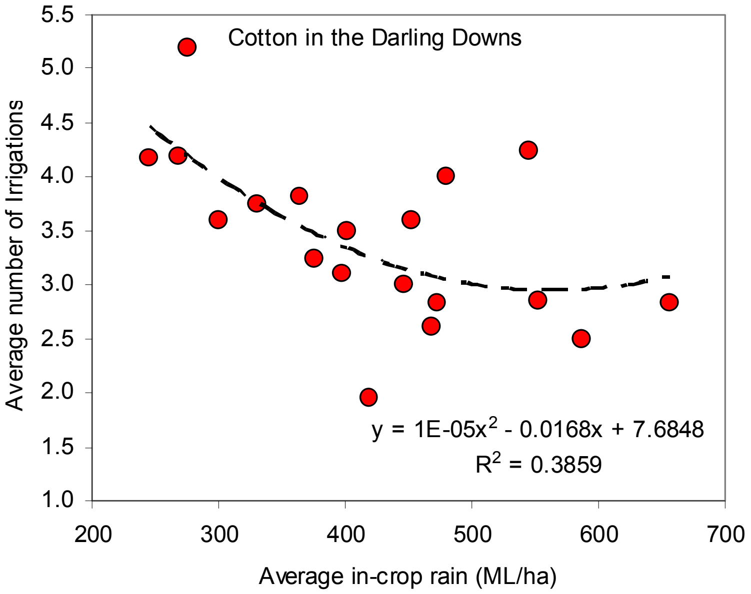

Figure 5 Average number of irrigations as a function of average in-crop rain for cotton, obtained from data provided by farmers participating in yield competitions in the Darling Downs, Australia, from 1987-2005.

Total water inputs (rain + irrigation) averaged 7.7 ML/ha (770 mm), but have been steadily decreasing since 2002 (Figure 6). This decrease could be due to increasing restriction in water supplies, to improved water management, or to a combination of both.

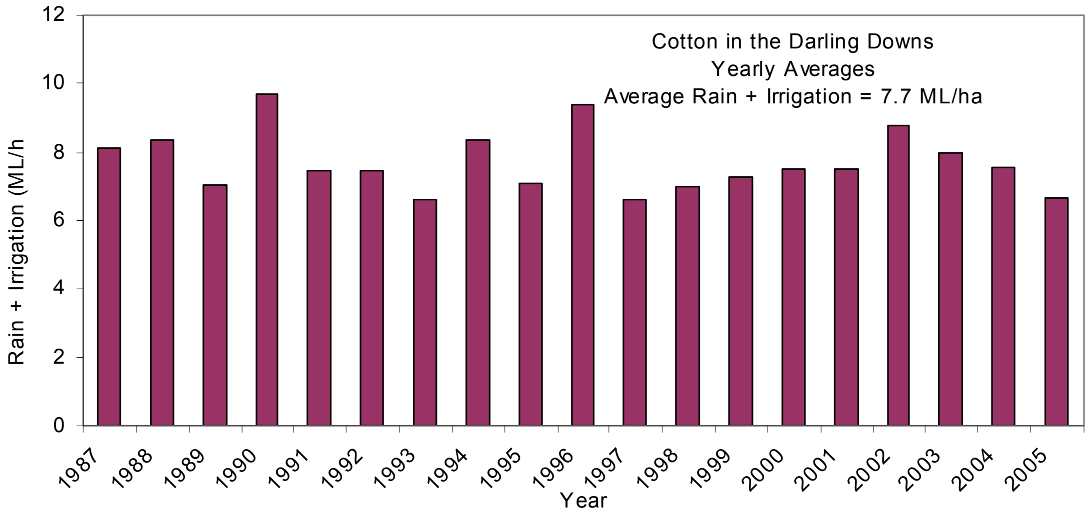

Figure 6. Average total water (rain + irrigation) for cotton by year, reported by farmers participating in yield competitions in the Darling Downs, Australia.

Lint yields show considerable variation from year to year, with an average of 9.34 bales/ha for irrigated and 4.83 bales/ha for dryland cotton (Fig. 7). Irrigated yields peaked in 2001, and have tended to steadily decrease in the last 5 years, which could be related to the decrease in water inputs (rain + irrigation) discussed above. Figure 8 suggests that on average for all years, lint yield tended to increase for (rain + Irrigation) ≤ 7.0 ML/ha, but limited yield increases resulted from additional water inputs. These results suggest that 7.0 ML/ha of (rain + irrigation) are enough to meet the crop water requirements and reach the yield potential in the area during most seasons. It could also mean that other yield limiting factors are present at higher water input levels.

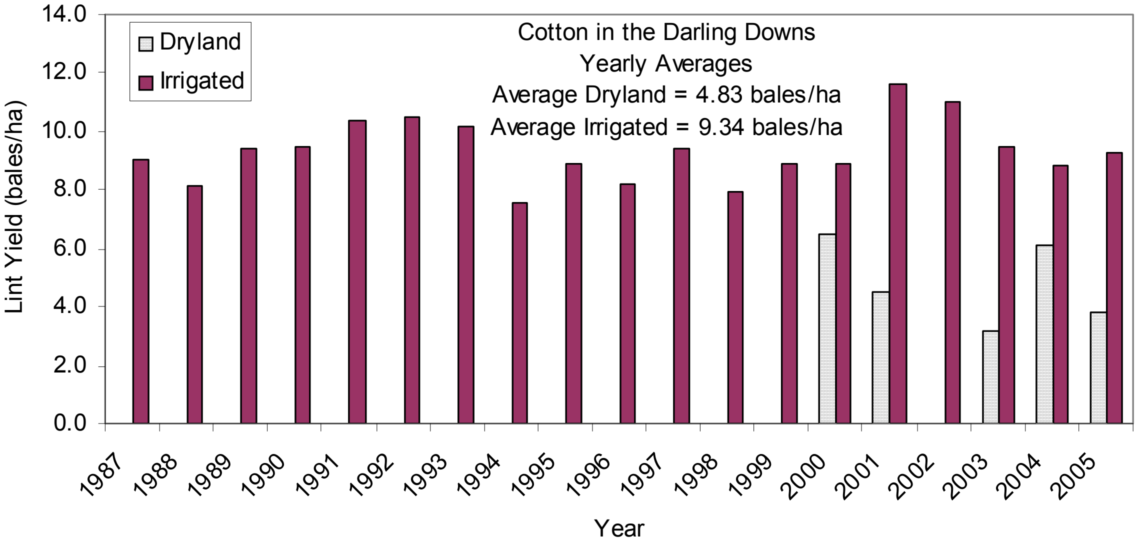

Figure 7. Average cotton lint yields by year, reported by farmers participating in yield competitions in the Darling Downs, Australia.

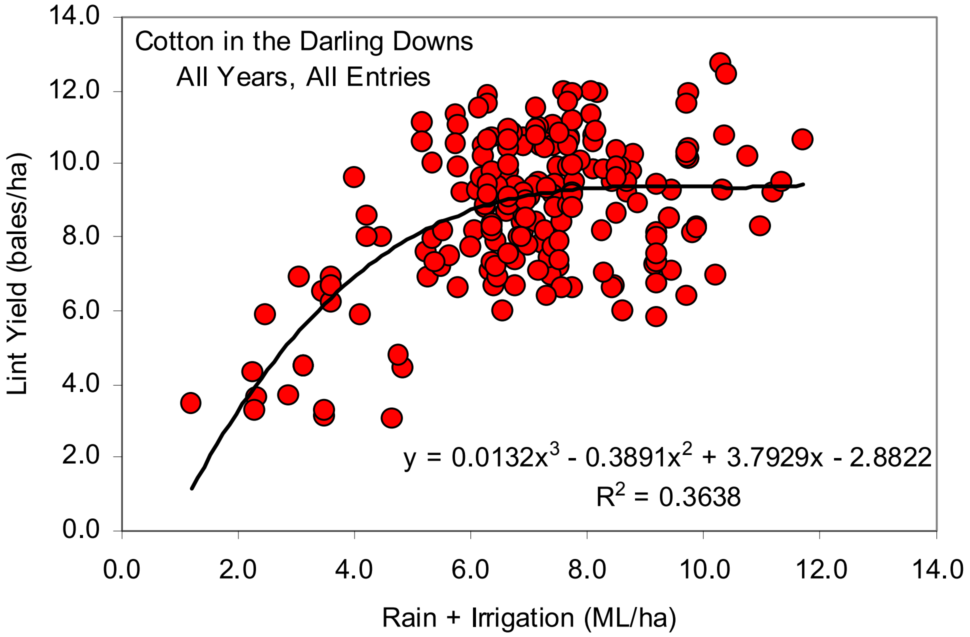

Figure 8 Cotton lint yield as a function of total water (rain + irrigation), obtained from data provided by farmers participating in yield competitions in the Darling Downs, Australia, from 1987-2005.

Water use efficiencies were calculated as gross production water use index [GPWUI=lint yield/ (rain +irrigation)] and also as irrigation water use index [IWUI = lint yield/ irrigation]. Since ET data were not available, the crop water use index [CWUI (lint yield/ET)] could not be calculated from this dataset. The GPWUI averaged 1.25 bales/ML for irrigated and 1.59 for dryland cropping systems, respectively (Figure 9). The GPWUI tended to decrease with the amount of (rain + Irrigation) (Figure 10). This decreasing trend suggests that in this area a positive dryland yield could be obtained even when (rain + irrigation) = 0, just relying on stored soil water at sowing.

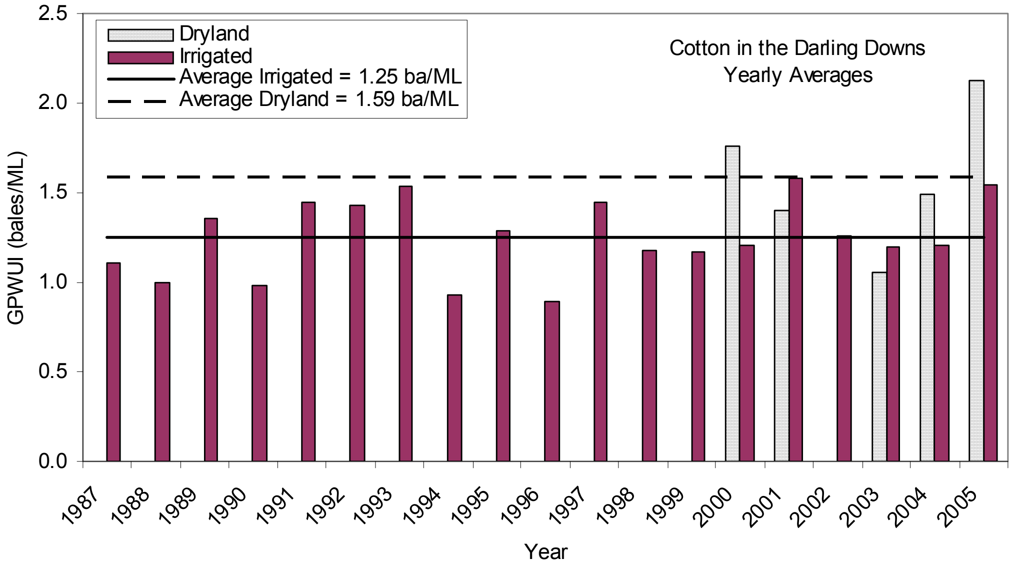

Figure 9 Average gross production water use index [GPWUI = (Lint yield)/(rain + irrigation)] for cotton by year, calculated from data provided by farmers participating in yield competitions in the Darling Downs, Australia.

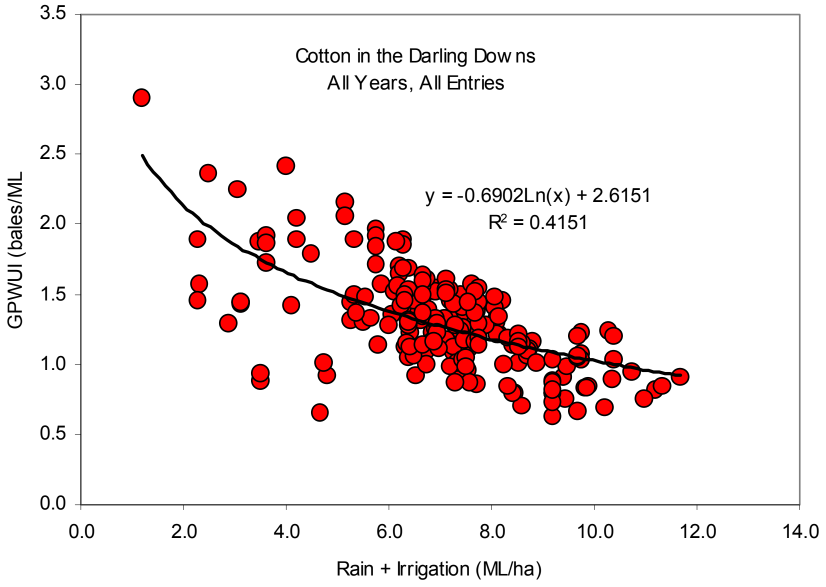

Figure 101. Gross production water use index [GPWUI = (Lint yield)/(rain + irrigation)] as a function of (rain + irrigation) for cotton, obtained from data provided by farmers participating in yield competitions in the Darling Downs, Australia, from 1987-2005

The IWUI values obtained by growers entering the competitions averaged 2.75 bales/ML of irrigation during the 1987-2005 period (Figure 11). These are very high values, indicating that in this area it is quite possible to reach the industry goal of increasing the industry average to 2.0 bales/ML of irrigation. The IWUI for individual entries, however, was well-related to irrigation and also tended to decrease with irrigation amount, ranging from around 2 to 12 bales/ML of irrigation (Figure 12). This wide range is not surprising given the sensitivity of the IWUI to in-crop rainfall and to irrigation amount discussed earlier. These values suggest that very high values are possible in wet years and/or in areas requiring little irrigation. For years requiring more than 3 ML/ha of irrigation the IWUI tended to level off at a value of approximately 2.0 bales/ML. The decreasing pattern of IWUI with irrigation follows the theory for areas and seasons with a positive dryland yield discussed earlier. Therefore, in this area IWUI can be increased by decreasing irrigation, even when the crop is stressed. That, of course, will reduce yields, total production, and will also reduce the CWUI. The effect of deficit irrigation on economic gross margins per unit area ($/ha), irrigation ($/ML) and at the whole-farm ($/farm) levels are discussed later in this report.

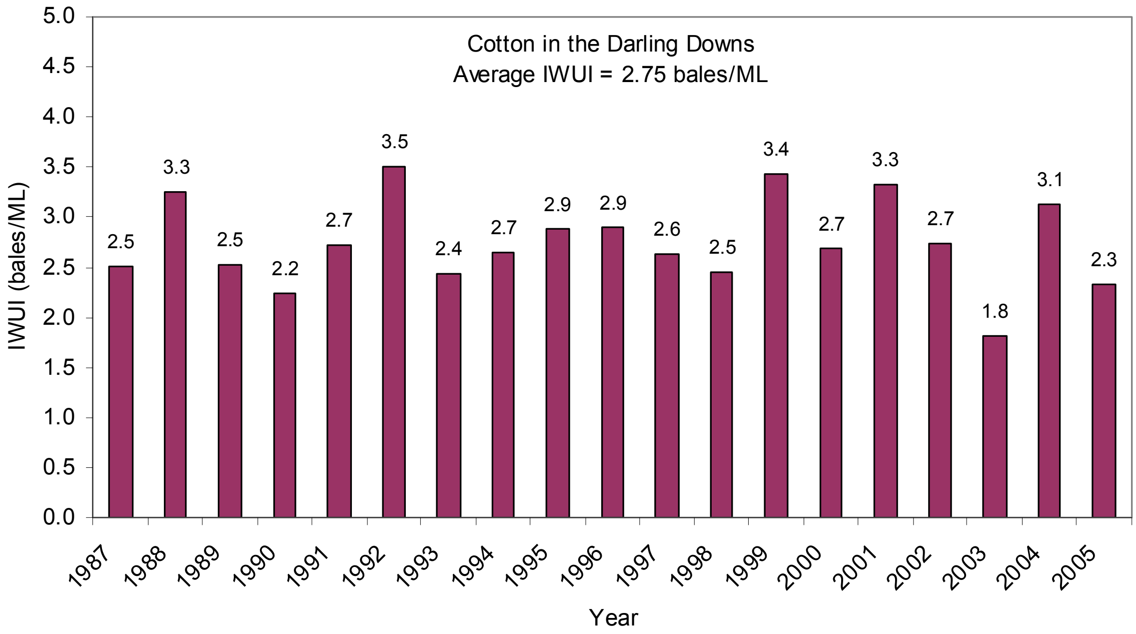

Figure 11 Average irrigation water use index (IWUI =lint yield/irrigation) for cotton by year, calculated from data provided by farmers participating in yield competitions in the Darling Downs, Australia.

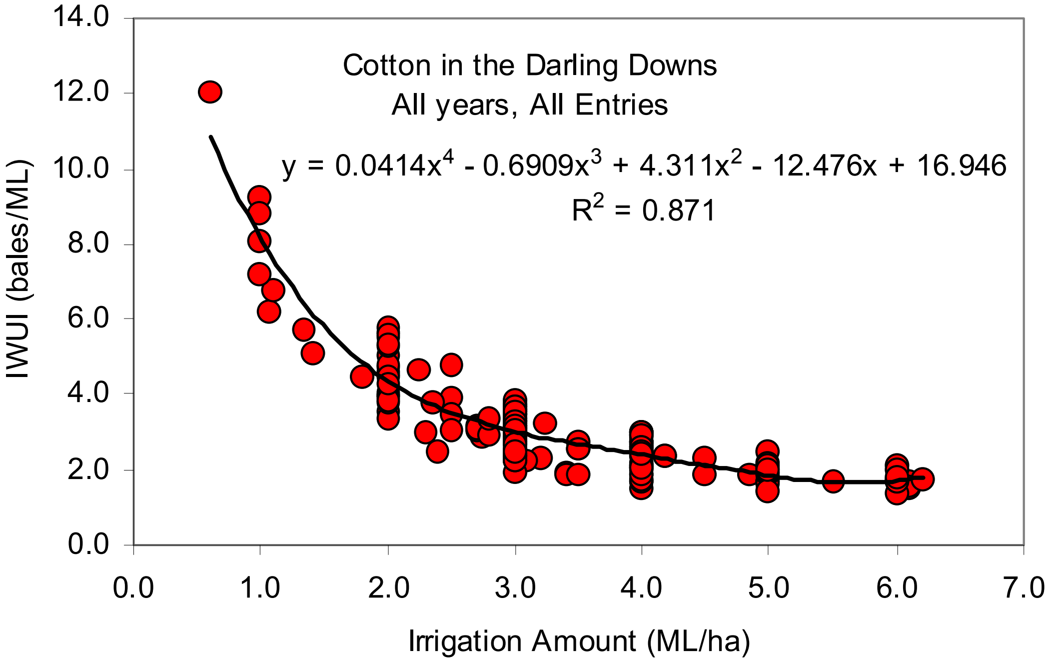

Figure 12 Irrigation water use index (IWUI = lint yield/irrigation) as a function of irrigation amount for cotton, obtained from data provided by farmers participating in yield competitions in the Darling Downs, Australia, from 1987-2005

The Cotton Catchment Communities CRC Water Team members were unable to identify the existence of Crop Competition Datasets other than those from the Darling Downs. The Darling Downs dataset was used by Dr Jose Payero in compiling the “Benchmarking Water Management in the Australian Cotton Industry” report.

Discussions with David Dowling of the Australian Cottongrower (co-ordinators of the Cottongrower of the Year Awards) revealed that there was little useful benchmark information available from this source. Little data was collected from participants on their water use and that which was collected was at best estimates only.

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Outcomes

The intended outcomes of the original project proposal have been met. The existing information on irrigation benchmarks within the Australian Cotton Industry have been documented in Payero, J.O. and Harris, G.A. 2008 "Benchmarking Water Management in the Australian Cotton Industry" – see Appendix 1. Two tools have been developed to aid the on-going collection of irrigation benchmark data across the industry into the future:

- Water Benchmarking Tool
- ISID – the Irrimate Surface Irrigation Database

Additionally, Aquatech Consulting have developed WaterTrack Rapid which is a more robust tool then the Water Benchmarking Tool for the collection of industry wide benchmark data. The original plan was for the Water Benchmarking Tool to be incorporated into the proposed e-BMP process so that this data could be collected and collated in an industry-wide fashion. It is possible that this could still happen but at present the e-BMP is still not available. Relying on irrigators to voluntarily provide their benchmark data through the Water Benchmarking Tool has to date been unsuccessful.

The use of WaterTrack Rapid for the collection of benchmark data on an annual basis may be a more useful way to collate this data. There are two possible ways this could be done:

- Cotton Consultants in each valley be engaged to collect this data annually from at least 10 of their growers for inclusion in an industry wide database. This approach has the advantage of enabling consultants to benchmark the performance of their growers and give them confidence in the use of a tool such as WaterTrack Rapid. The industry will need to pay for this annually but the result will be the collection of a standardised dataset of irrigation benchmark performance measures.
- Each year a survey be conducted using WaterRapid using a single consultant (in much the same manner as that conducted by David Williams, NSW DPI for the 2005-06 season). This has the advantage of ensuring a consistent approach to using WaterTrack Rapid but would likely reduce the number of participating growers compared to what should be achievable with the former suggestion.

The development of ISID provides a further opportunity for the industry to collect useful information on the improvements in surface irrigation performance being achieved within the industry. To reach its full potential funding must be committed to ensure the ongoing collection of the results of commercial Irrimate evaluations. This will ensure the integrity of the results and a long-term view of the improvements the industry is making. This funding should go to the NCEA to provide this service and provide an annual report to industry on surface irrigation performance.

Conclusion

The review of available data shows tremendous variability in water use indices, both in Australia and overseas. This variability is due to several factors, including the lack of consistency on the procedures used to evaluate WUE, especially in measuring or estimating the "water" terms. Also, the differences in net irrigation requirements and yield potential among locations make it difficult to fairly compare different datasets.

In general, Australia produces the highest cotton yields in the world, or at least it is among the leaders, depending of the source of statistics consulted. However, the review of available data shows that irrigation efficiencies of the predominant surface irrigation systems can still be improved. Therefore, there is the potential for further improvements in WUE by focussing on increasing irrigation efficiency. Also, since considerable water losses occur during storage and distribution systems, the focus should be on improving efficiency at the whole-farm level, and not only at the field scale. It is evident that the industry is currently taking steps in this direction. Examples are the development and uptake of furrow evaluation and optimization technology, and the increasing use of overhead sprinkler irrigation (centre pivots and lateral move machines) in the cotton industry.

The lack of good annual and robust benchmark data is an issue that the cotton industry and irrigation sector in total needs to address. This project has resulted in the development of the following benchmark tools:

- Water Benchmarking Tool
- ISID – the Irrimate Surface Irrigation Database

Indirectly it has also resulted in the development of the WaterTrack Rapid tool by Aquatech Consulting. It is now up to industry to progress the use of these tools to en hance the ongoing collection of robust irrigation benchmark data.

Extension Opportunities

The results of the review of water use efficiency benchmarks within the cotton industry should be promoted widely. This has already happened within the industry via the publications listed below. There may well be an opportunity to promote it more widely to the general public although some caution is needed here owing to the political sensitivities around the issue of water use by the cotton industry.

The industry must invest in the use of the new benchmark tools in a way that will provide ongoing collation of this information to document the progress being made in improving water use efficiency.

Publications

Gillies, M.H. 2008 Benchmarking Water Management in the Australian Cotton Industry, National Centre for Engineering in Agriculture Publication 1002691/2, USQ, Toowoomba

Gillies, M.H. & Curran, N (2008). ISID Irrimate Surface Irrigation Database - User Manual and Technical Documentation. National Centre for Engineering in Agriculture Publication 1002691/1, USQ, Toowoomba.

Harris, G.A. 2007 Benchmarking Water Management in the Australian Cotton Industry, Spotlight on Cotton R&D – Summer 2007, CRDC, p6

Harris, G.A. 2007 Water Use Efficiency – What is it? And How do we measure it?, Spotlight on Cotton R&D – Summer 2007, CRDC, p7

Payero, J.O. 2007 Do you know your water use efficiency?, Downs Water Chat 6, 10 April 2007, DPI&F

Payero, J.O. 2007 Do you know your water use efficiency? More Profit per Drop Issue 1, DPI&F Irrigated Farming Systems Team

Payero, J.O., McIntyre, G. and Harris, G.A. 2007 Darling Downs crop competitions show very high water use efficiencies, Spotlight on Cotton R&D – Summer 2007, CRDC, p13-14

Payero, J.O. and Harris, G.A. 2008 An overview of Cotton Water Use Efficiency in Australia, Benchmarking Water Use Efficiency in the Australian Cotton Industry. in Darling Downs District Cotton Trial Book 2000-2007, Kate Charleston (ed), DPI&F, Dalby

Payero, J.O. and Harris, G.A. 2008 “Benchmarking Water Management in the Australian Cotton Industry”, Cotton Catchment Communities CRC and DPI&F

Part 4 – Final Report Executive Summary

This project has collated the current information on water use by the cotton industry and the improvements in irrigation management that have occurred and are continuing to be implemented by the industry. It has also provided an overview of water benchmarking concepts.

The review of available data shows tremendous variability in water use indices. This variability is due to several factors, including the lack of consistency on the procedures used to evaluate WUE, especially in measuring or estimating the "water" terms. Also, the differences in net irrigation requirements and yield potential among locations make it difficult to fairly compare different datasets. Since 2000-01 the Australian Cotton industry has improved

In general, Australia produces the highest cotton yields in the world. Since 2000-01 there has been a 29 per cent improvement in the Irrigation Water Use Index for the industry (from 1.10 bales/ML to 1.43 bales/ML in 2006-07). This is a single index only and a number of benchmark indices must be considered to truly reflect the efficiencies within the industry. The review of available data shows that irrigation efficiencies of the predominant surface irrigation systems can still be improved. Therefore, there is the potential for further improvements in WUE by focussing on increasing irrigation efficiency. Also, since considerable water losses occur during storage and distribution systems, the focus should be on improving efficiency at the whole-farm level, and not only at the field scale. It is evident that the industry is currently taking steps in this direction. Examples are the development and uptake of furrow evaluation and optimization technology, and the increasing use of overhead sprinkler irrigation (centre pivots and lateral move machines) in the cotton industry.

The lack of good annual and robust benchmark data is an issue that the cotton industry and irrigation sector needs to address. This project has resulted in the development of the following benchmark tools:

- Water Benchmarking Tool
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Indirectly it has also led to the development of the WaterTrack Rapid tool by Aquatech Consulting. It is now up to industry to progress the use of these tools to enhance the ongoing collection of robust irrigation benchmark data.

Further details on the results of this project can be obtained by contacting Graham Harris, Dept of Primary Industries and Fisheries/Cotton Catchment Communities CRC, PO Box 102, Toowoomba, Q. 4350 Phone: 07 46881559 E-mail: graham.harris@dpi.qld.gov.au.

APPENDICES

Appendix 1 – Review of Water Use Efficiency Benchmarks in the Australian Cotton Industry

Appendix 2 - Cotton Water Use Efficiency Study (re-survey of Sunnil Tennakoon and Steve Milroy's 1990s study)

Appendix 3 - Gillies, M.H. 2008 Benchmarking Water Management in the Australian Cotton Industry, National Centre for Engineering in Agriculture Publication 1002691/2, USQ, Toowoomba

Appendix 4 – Gillies, M.H. & Curran, N. 2008 ISID Irrimate Surface Irrigation Database - User Manual and Technical Documentation. National Centre for Engineering in Agriculture Publication 1002691/1, USQ, Toowoomba

Appendix 5 - Questionnaire: Using HydroLOGIC to benchmark water use

APPENDIX 1

Review of Water Use Efficiency Benchmarks in the Australian Cotton Industry

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Queensland Department of Primary Industries and Fisheries
November 2008

Cotton Catchment Communities CRC

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Executive Summary

It has been suggested that the cotton industry has gone close to doubling its water use efficiency (WUE) over the last decade, mainly by increasing yield per unit area (bales/ha), and a new challenge to "*double again the WUE by 2015*" has recently been proposed. Some important questions, however, are:

- Where is the industry now in terms of WUE and how does it compare to other water users – nationally and internationally?
- How is the industry going to know when the WUE has doubled?
- What tools and processes does the industry have to capture, analyse and report WUE information?

The Benchmarking Water Management in the Australian Cotton Industry project was established with the objectives of:

- Collating and publishing existing information on WUE benchmarks within the Australian Cotton industry
- Implementing strategies to gather and report on cotton industry WUE benchmarks annually

This report is part of this benchmarking process and collates the existing information on WUE within the Australian cotton industry and in selected international sites. The report starts with an overview of water use in Australia by agriculture and other sectors, and presents a brief description of the Australian cotton industry, especially focussing on how the industries uses irrigation water and how it has been affected by the current drought.

Then, definitions of benchmarking, and the concepts of water use efficiency and water use indices are discussed. Next, different challenges for effective benchmarking are presented, including the ambiguities inherent to the water use efficiency concept. The report explains that WUE can be increased in many ways (i.e. increasing yield, decreasing water inputs, or both) and how important it is for the industry to clearly define how the WUE is to be increased. It then discusses the need to clearly define what measure of WUE the industry wants to increase. Choices include biophysical or economic measures of WUE. The biophysical measures include water use indices (expressed in bales/ML) such as the:

- Crop Water Use Index (CWUI) = yield/evapotranspiration;
- Gross Production Water Use Index (GPWUI) = yield/total water; and the,
- Irrigation Water Use Index (IWUI) = yield/irrigation.

Economic measures of WUE include water use indices that measure economic return (i.e. profit, net return, gross margin) per unit of water input ($/ML). It is emphasized that water management strategies needed to maximize bales/ML or bales/ha would be different that those needed to maximize $/ha or $/ML, and thus the importance of having a well defined objective.

The report then focuses on the importance of using water use indices that allow comparison among seasons and locations. The IWUI is shown not to be a good benchmarking index since it is highly variable with season and location and it is therefore not necessarily a good indicator of good water management. The variability in IWUI is due to the fact that the yield versus irrigation response function for a given location is not unique and is very dependent on rainfall. A theoretical discussion on how IWUI changes with irrigation is presented based on the assumption that yields increase approximately linearly with irrigation up to the point where irrigation becomes excessive. The CWUI is shown to be much more stable among seasons and locations than the IWUI and the reasons why are discussed. However, it was also shown that the CWUI also has some shortcomings as a benchmarking index, mainly due to the fact that the amount of evapotranspiration needed to obtain a given yield varies with season and location. It was suggested that to allow comparison among seasons and locations, the ideal water use index needs to be based on net irrigation water requirements and also consider differences in yield potential among seasons and locations. A new water use index is proposed.

Following the conceptual discussions, the available WUE data is presented. First the data from Australia, followed by data from selected sites around the world. Also, data on international comparisons of cotton WUE are presented. This report includes data at several scales and with varying quality. It includes WUE data at the international, national, valley, farm, and field levels. It also includes a review of research data at the plot-size scale, and also data collected by farmers and crop consultants at the commercial production scale. Data differ in quality since some of them were measured while others were estimated. Differences in the calculated water use indices also arise from the fact that data collected from different applications did not necessary follow the same measurement and estimation procedures..

The review of available data shows tremendous variability in water use indices, both in Australia and overseas. This variability is due to several factors, including the lack of consistency on the procedures used to evaluate WUE, especially in measuring or estimating the “water” terms. Also, the differences in net irrigation requirements and yield potential among locations make it difficult to fairly compare different datasets. In general, Australia produces the highest cotton yields in the world, or at least it is among the leaders, depending of the source of statistics consulted. However, the review of available data shows that irrigation efficiencies of the predominant surface irrigation systems can still be improved. Therefore, there is the potential for further improvements in WUE by focussing on increasing irrigation efficiency. Also, since considerable water losses occur during storage and distribution systems, the focus should be on improving efficiency at the whole-farm level, and not only at the field scale. It is evident that the industry is currently taking steps in this direction. Examples are the development and uptake of furrow evaluation and optimization technology, and the increasing use of overhead sprinkler irrigation (centre pivots and lateral move machines) in the cotton industry. The report ends with a discussion on how to improve WUE, focusing on the IWUI, the CWUI, and also presents a discussion on how to increase profits per unit area ($/ha), per unit irrigation ($/ML), and for the whole farm ($/farm).

Introduction

The current drought is focussing the attention of the Australian community on the use of water by the irrigation sector. The Cotton Industry has been specifically targeted through extensive coverage in the media as a gross user of water. The industry needs to evaluate its current irrigation water use and management, and use this to identify opportunities for potential improvements. As part of this process there is a need to collate the current information on water use by the industry and the benefits it has for regional communities and for the nation. In addition it is necessary to demonstrate the improvements in irrigation management that have occurred and are continuing to be implemented by the industry. At the same time the industry needs to be confident that it is making every possible effort to manage water as efficiently as possible. It needs to monitor the on-going improvements resulting from its past and current investments in water management R,D&E. This report is part of a benchmark process with the objectives to:

1. Collate and publish existing information on irrigation management benchmarks within the Australian Cotton industry
2. Implement strategies to gather and report on cotton industry water management benchmarks in an on-going way to monitor performance of the industry.

It documents the cotton industry's use and management of irrigation water at the national, farm and field scale. It presents the available water use efficiency (WUE) information on the cotton industry in context with all Australian irrigation sectors and benchmarks its performance with international competitors.

Agricultural water use in Australia

The National Water Commission (2007) recently reported that, agriculture used approximately 65% of the water consumed in the Australian economy in 2004/05 (Table 1), 91 % of which was used for irrigation. The major users of irrigation water in Australia for that year are shown in Fig. 1 (Australian Bureau of Statistics, 2006d). It shows that the most extensive use of irrigation water was on pasture for grazing (28%) followed by cotton (18%) and sugar cane (12%).

Table 1 Water use by sector in Australia in 2004/05 (National Water Commission, 2007)

Water User	Water use (GL)	Water use (%)
Agriculture	12,191	65%
Household	2,108	11%
Water Supply Industries	2,083	11%
Other Industries	1,330	7%
Manufacturing	589	3%
Mining	413	2%
Total	18,714	

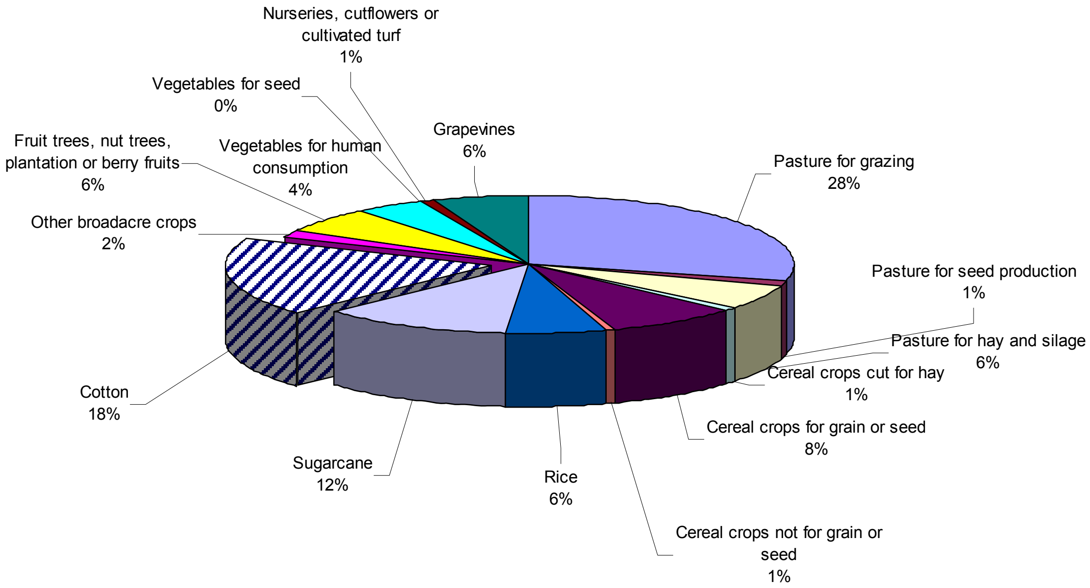


Figure 1. Water use for irrigated agriculture in Australia in 2004/05 (Australian Bureau of Statistics, 2006d)

The percentage of agricultural establishments irrigating in Australia was 27%, which was a 12.8% decrease compared to 2003-04. The total area irrigated, however, stayed stable at about 2.4 million hectares. The total volume of water used for irrigation fell 3.4% from 10,442 GL in 2003-04 to 10,085 GL in 2004-05. During this period, there was a substantial increase in the volume of water used for irrigation of cotton (up by 570 GL), with decreases occurring in pasture for hay and silage (down by 206 GL), rice (down by 195 GL), and pasture for grazing (down by 188 GL). Irrigation of cotton increased significantly during 2004-05, with both the area irrigated and volume of water used increasing from the previous year.

The area irrigated and irrigation applied by different crops and pastures in Australia for the 2002/03, 2003/04, and 2004/05 seasons are shown in Table 2 and Fig. 2, respectively (Australian Bureau of Statistics, 2005a, 2005b, and 2006d). Agricultural land in Australia is predominantly occupied by pasture for grazing, which in 2004/05 represented about 86% of the total agricultural area. In terms of area, cotton occupies a minute portion of the total agricultural land in Australia (<0.1%). However, pasture for grazing is predominantly rainfed, with only 0.2% of it irrigated, while cotton is predominantly irrigated (88.8% in 2004/05). The total area of irrigated pasture for grazing, however, is still more than three times that of irrigated cotton.

The Australian Bureau of Statistics (2006c) reported that the average irrigation rate in Australia was 4.2 ML/ha, which varied considerably with crop, as shown in Fig. 2. Rice had the highest irrigation rate at 12.1 ML/ha, followed by cotton at 6.7 ML/ha. However, in terms of total volume of water used, pasture for grazing is by far the major user of irrigation water, using almost twice as much total volume of water as cotton (Fig. 2). Because of the large area planted to pasture for grazing, it uses the largest volume of irrigation water compared to other crops, despite the fact that only a very small percentage (≈ 0.2%) of pasture land is irrigated (Table 2). The Australian Bureau of Statistics (2006c) also reported that just over one-third of irrigators irrigated pasture for grazing, while only 1.9% irrigated cotton and 6.4% irrigated sugar cane. Surface water was the predominant source of irrigation water, representing nearly three quarters of all the water used in agriculture. Groundwater was the other major source of water. Surface irrigation was the most common irrigation method used in Australia, with 30.4% of irrigated agricultural establishments using this method. Surface irrigation also represented 60.2% of the area irrigated.

Due to the current drought, both the cotton area planted and water used have decreased significantly since 2000-01. Figure 3 shows that the volume of irrigation water used for cotton production in 2004-05 decreased by about 37% compared to the 2000-01 level. Data for 2006/07 are not yet available, but when available would likely show further decreases in water use by cotton.

Table 2. Area of irrigated crops and pastures in Australia. Adapted from Australian Bureau of Statistics (2005a, 2005b, and 2006d)

	Area Under Crop and Pasture ('000 ha)			Area Irrigated ('000 ha)			Area Irrigated (%)		
Crop/Season	**02/03**	**03/04**	**04/05**	**02/03**	**03/04**	**04/05**	**02/03**	**03/04**	**04/05**
Pasture for grazing	341,336	367,634	382,306	710	784	842	0.2%	0.2%	0.2%
Pasture for seed production	91	144	161	32	32	33	35.2%	22.2%	20.5%
Pasture for hay and silage	740	1,048	1,021	162	198	151	21.9%	18.9%	14.8%
Cereal crops cut for hay	505	603	579	66	43	33	13.1%	7.1%	5.7%
Cereal crops for grain or seed	17,351	20,148	20,533	365	326	309	2.1%	1.6%	1.5%
Cereal crops not for grain or seed	841	757	923	42	28	19	5.0%	3.7%	2.1%
Rice	46	66	51	44	65	51	95.7%	98.5%	100.0%
Sugarcane	568	559	533	238	241	213	41.9%	43.1%	40.0%
Cotton	**245**	**227**	**304**	**234**	**185**	**270**	95.5%	81.5%	88.8%
Other broadacre crops	3,540	3,198	3,380	68	89	63	1.9%	2.8%	1.9%
Fruit trees, nut trees, plantation or berry fruits	187	172	165	138	120	122	73.8%	69.8%	73.9%
Vegetables for human consumption	121	126	123	112	116	109	92.6%	92.1%	88.6%
Vegetables for seed	6	5	5	4	5	5	66.7%	100.0%	100.0%
Nurseries, cutflowers or cultivated turf	16	16	16	13	16	14	81.3%	100.0%	87.5%
Grapevines	157	164	163	150	149	147	95.5%	90.9%	90.2%
Total	**439,531**	**440,110**	**445,149**	**2,378**	**2,402**	**2,405**	**48.1%**	**48.8%**	**47.7%**

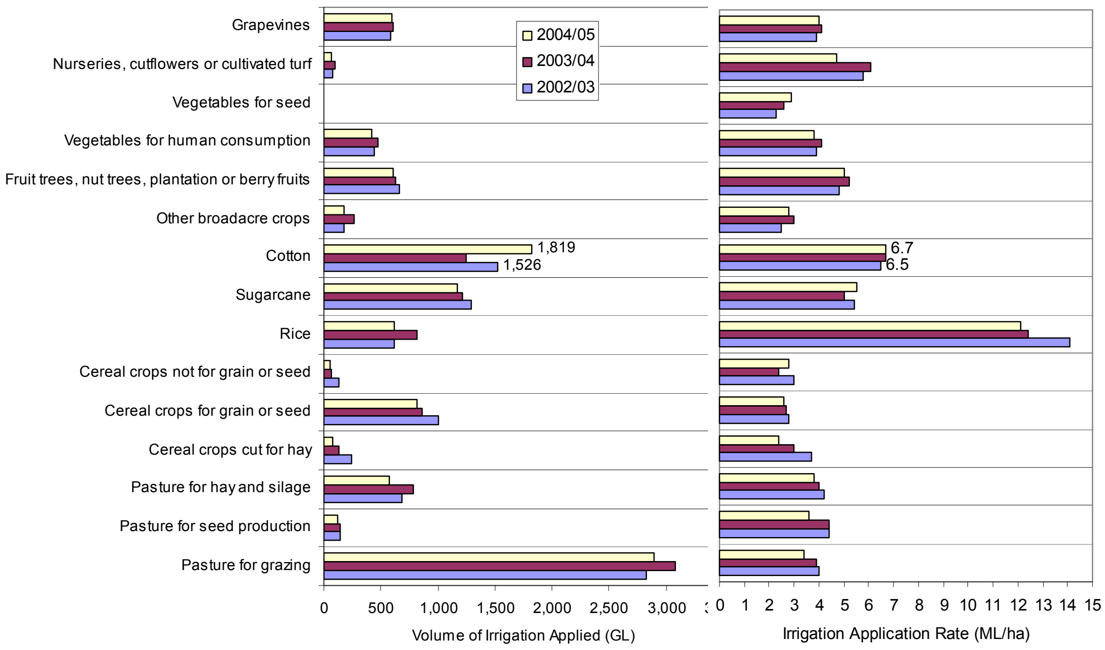


Figure 2. Irrigation application rate by crops and pastures in Australia. Adapted from Australian Bureau of Statistics (2005a, 2005b, and 2006d)

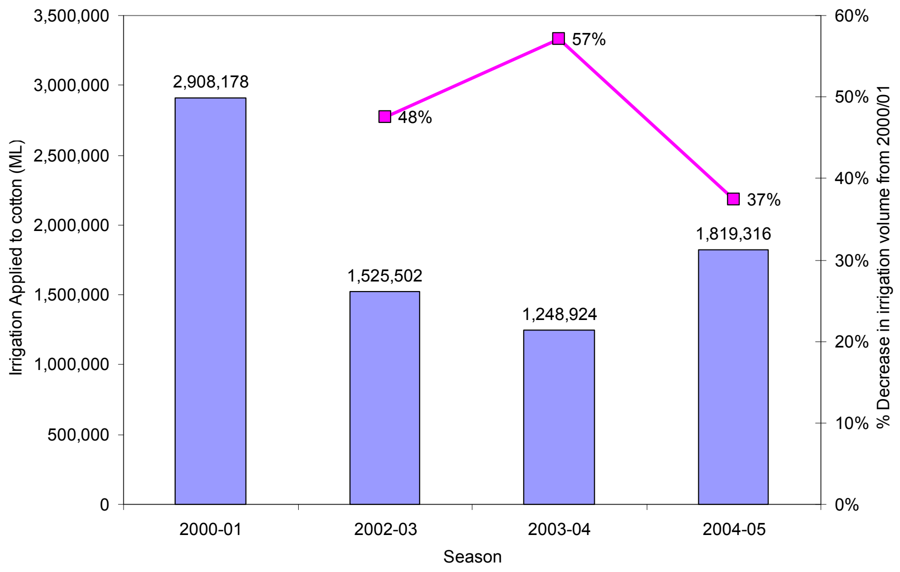


Figure 3. Volume of irrigation applied to cotton during 2000-01 to 2004-05 and decrease in volume of irrigation applied to cotton compared to the 2000-01 season (Australian Bureau of Statistics 2004, 2005a, 2005b, and 2006d). Data for 2001-02 were not available.

The Australian Cotton Industry

The Australian cotton industry is among the world leaders in yield and fibre quality. In Australia, cotton production is concentrated in the Eastern part of the country, where the industry is distributed in several river valleys in the states of New South Wales (NSW) and Queensland (Table 3). Approximately 70% of Australia's cotton is grown in NSW and the remainder in Queensland (Roth, 2006). According to Cotton Australia (2007), nearly all Australian cotton is grown in the Murray-Darling Basin.

Table 3. Australia cotton producing areas. Adapted from The Australian Cotton Grower: Cotton Yearbook 2006 (McCormack et al., 2006).

Cotton Producing Area	No. of cotton Gins	State	Main Rivers	Main Towns
Central Highlands	2	QLD	Mackenzie	Emerald
Dawson-Callide	1	QLD	Dawson Callide	Theodore, Biloela
St. George-Dirranbandi	2	QLD	Balonne	St. George, Dirranbandi
Darling Downs	3	QLD	Condamine	Toowoomba, Pittsworth, Cecil Plains, Dalby
MacIntyre Valley	5	NSW/ QLD	MacIntyre Boomi	Goondiwindi, Mungindi
Southern NSW	1	NSW	Lachlan	
Gwydir Valley	8	NSW	Gwydir	Collarenebri, Moree
Upper Namoi Valley	2	NSW	Namoi Mooki	Boggabri, Gunnedah
Lower Namoi Valley	6	NSW	Namoi	Walgett, Wee Waa, Narrabri
Bourke		NSW		Bourke
Macquarie Valley	4	NSW	Macquarie	Warren, Trangie, Narromine

Cotton in Australia is irrigated with surface water sources (from regulated and unregulated streams and rivers), groundwater, and water harvested on-farm that comes from overland flow created by occasional storms. The proportion from each water source varies with region and season. Results of a survey conducted by Doyle and Coleman (2007) for the 2005-06 season showed an estimate of the percentages of irrigation water from each source (excluding water harvested on-farm) for each of four cotton producing regions (Fig. 4). It should be kept in mind, however, that these results only reflect the situation of farmers responding the survey, which represented less than 19% of the area of cotton planted that year. Surface water has been the main source of water for cotton production. During the drought, the availability of surface water has been limited and groundwater is gaining importance. Since groundwater needs to be pumped, it is usually a more expensive than surface water and water captured on-farm, although it is more reliable.

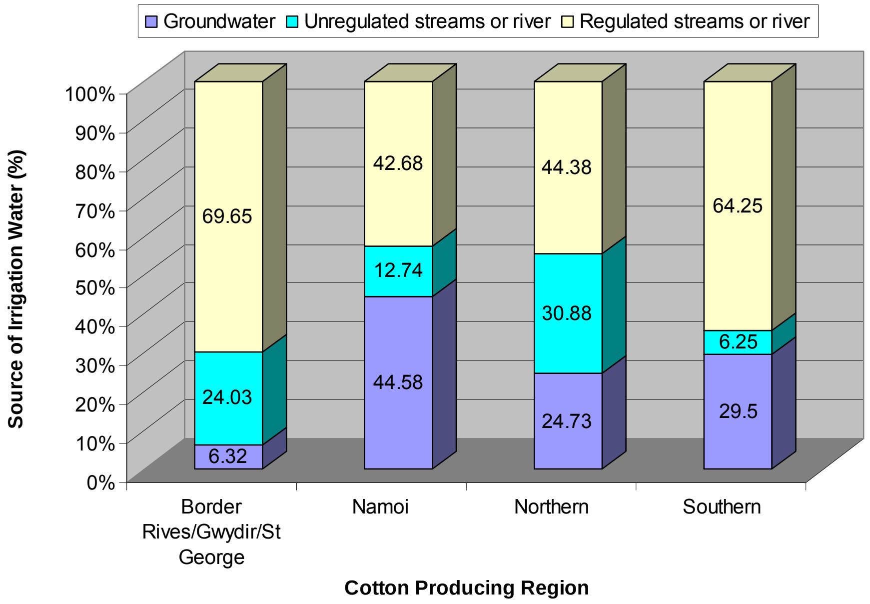


Figure 4. Volume Sources of irrigation water for cotton production by region for the 2005-06 season. Data was obtained from a survey conducted by Doyle and Coleman (2007).

In the Australian cotton industry, surface water is delivered from the dams and weirs to the farms via rivers, streams, or artificial channels. Most irrigated cotton land in Australia is located close to rivers. On the farms, the water delivered is usually stored in large earthen storages locally known as "ring tanks" (Fig. 5). The ring tanks are also used to capture over-land flow from storms that result in short-term run-off. The ring tanks are usually large, unlined, and open to the atmosphere. Since water, when available, has to be stored on-farm for long periods of times, storage losses from seepage and evaporation can be significant. From the ring tanks, water is usually delivered to the fields to be irrigated via unlined channels. At the field level, irrigation is usually applied using furrow irrigation with siphon tubes (Fig. 6). In some areas, a few farmers also use "siphon-less," or "bank-less" irrigation systems (Harris, 2006; Hood and Carrigan, 2006). Typically, irrigation is applied to furrows using continuous flow. Gated pipes and surge flow systems are practically not used in the Australian cotton industry. Since fields are usually large, nearly flat, and with very heavy clay soils, furrows can be quite long. Runoff water from the field is usually captured and reused on farm.

Recently, some cotton producers have been changing from furrows to alternative irrigation systems, mainly to overhead sprinkler machines, like lateral move and centre pivots to improve irrigation efficiency (Fig. 7) as an alternative for dealing with limited water. Because of the rectangular shape of the fields, lateral move systems are more common than centre pivots, despite being more difficult to manage. Drip irrigation, mainly subsurface drip irrigation (SDI), is used on some farms (Fig. 8). However, the cotton area irrigated by sprinkler and drip systems is still very small compared with surface systems. Water and labour shortages have been the main drivers that have motivated some farmers to change from surface to alternative irrigation systems. However, questions about the economic feasibility of the alternative irrigation systems, especially in an environment of uncertain water supplies and low cotton prices still remain. Additional irrigation characteristics of farms with cotton as the main irrigated activity are shown in Table 4 (Australian Bureau of Statistics, 2006a).

Figure 5. Aerial photograph showing farm storages ("ring tanks") in the Darling Downs, Australia (photo by Graham Harris).

Figure 6. Furrow irrigation system using siphon tubes at Narrabri, Australia (photo by Jose Payero).

Figure 7. Overhead sprinkler machine in the Darling Downs, Australia (photo by Jose Payero).

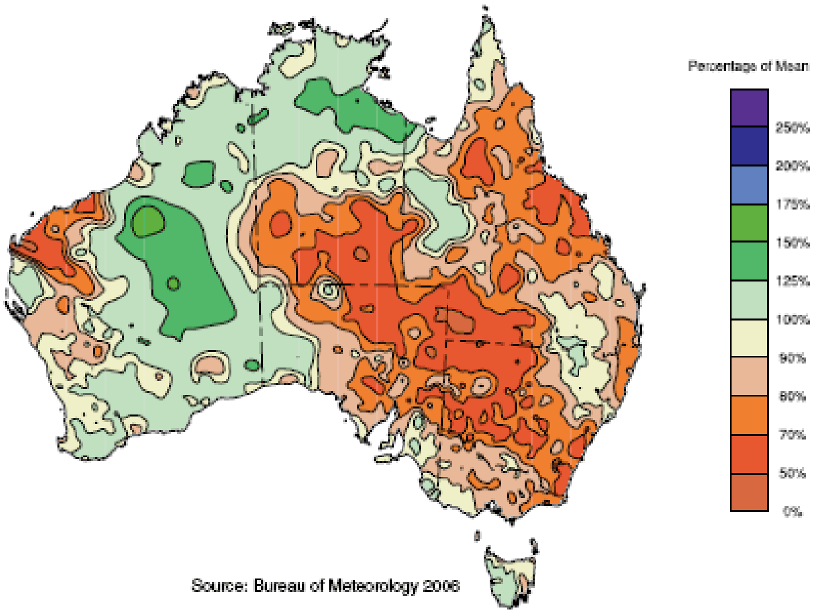
Figure 8. Some of the components of a Subsurface drip irrigation (SDI) system installed in a farm near Emerald, Australia (photo by Jose Payero).

Table 4. Irrigation characteristics of farms with cotton as the main irrigated activity for the 2002-03 and 2003-04 seasons. Adapted from data reported by the Australian Bureau of Statistics (2006a).

	Units	**2002-03**	**2003-04**
Use of Land and Water Resources			
Area of holding	ha	4,387	4,404
Area irrigated (farm)	ha	494	404
Area irrigated (main activity)	ha	414	343
Water use (farm)	ML	2,922	2,541
Water use (main activity)	ML	2,697	2,334
Water use intensity (main activity)	ML/ha	6.1	6.0
Farm dam capacity	ML	3,269	
Gross production returns & expenses			
EVAO (farm) *	$	$1,559,000	$1,636,000
GVP (farm)	$	$1,776,000	$1,795,000
GVIP(main activity)	$	$1,447,000	$1,184,000
GVIP (farm)	$	$1,520,000	$1,265,000
	$/ha	$2,990	$3,180
	$/ML	$642	$762
Irrigation expenses	$/ML	$133	
Water license	%Total	11%	
Volumetric charges	%Total	17%	
Irrigation fees	%Total	3%	
Equipment purchase	%Total	15%	
Operating expenses	%Total	39%	
Construction	%Total	13%	
Irrigation Investment > $100,000	%farms	78%	
Irrigation methods & practice			
Surface methods	%area irrigated	93%	95%
Drip/trickle methods	%area irrigated	0%	3%
Sprinkler methods	%area irrigated	6%	2%
Laser levelled land	%area holding	34%	
Water recycling	%farms	90%	

*EVAO = expected value of agricultural output, GVP=gross value of production, and GVIP=gross value of irrigated production.

Irrigation water is a vital component of the Australian cotton industry. Currently, the industry is facing serious limitations in irrigation water supplies, which are mainly the result of what has been called "*the worst drought in Australia since records began"* (Howard, 2007). The drought has been especially severe in most of the Eastern part of the country, where cotton is produced (Fig. 9).



Source: Bureau of Meteorology 2006

Figure 9. Percentage of mean annual rainfall 2002-03 to 2004-05 (Australian Bureau of Statistics, 2006b).

Water shortages are seriously affecting the cotton industry and have become the main factor limiting both the area planted and crop productivity. It has been suggested that the growth potential of the Australian cotton industry depends on the availability of water and that some restriction to growth faced by the industry could be overcome if water was available or if the cotton crop made more efficient use of water (DPI&F South Regional Management Team, 2006). The reduction in water supplies and its impact on the Australian cotton industry are illustrated in Table 5. Reduction in the cotton area due to lack of water in the 2006-07 season compared with 2001-02 averaged 59% and 71% for New South Wales and Queensland, respectively (Cotton Australia, 2007).

Although water scarcity is having a tremendous impact on agriculture, including cotton production, it has also impacted water supplies for the domestic, environmental, and industrial sectors. Water scarcity is increasing competition for limited water resources both within each sector and among sectors. Water markets are already in place for permanent or temporary (seasonal) trading of irrigation water entitlements in Australia (Shi, 2006). According to the Australian Bureau of Statistics (2006c), in 2004-05, extra water was purchased by 5% of agricultural establishments in Australia, while 3.7% of agricultural establishments sold water. The number of establishments buying extra water increased by 4% from the previous year, while the number of establishments selling water increased by 8.2%. Similar water markets could develop among sectors, which may include the transfer of water from agriculture to domestic, industrial, and environmental uses. In a water-trading environment, water prices would be expected to respond to market forces and, where practical, water will most likely flow towards the sectors in which it represents the highest economic value. In other words, water will tend to move from low-value, high-use enterprises to those with higher economic returns per unit water ($/ML).

Table 5. Magnitude of reduction in water supplies and its impact on the Australian cotton industry. Adapted from data reported by Cotton Australia (2007).

State	Location	% Cotton Area Reduction [a]	River Valley	% water Available [b]	Announced 2006-07 Allocation
NSW	Mungindi	44%	Murray	27%	0%
	Gwydir	59%	Murrumbidgee	12%	15%
	Walgett	93%	Macquarie	28%	0%
	Bourke	99%	Namoi	20%	0%
	Lower Namoi	42%	Gwydir	20%	0%
	Upper Namoi	34%	Border Rivers	45%	0%
	Macquarie	73%	Lachlan	15%	0%
	Lachlan/Murrumbidgee	58%			
	Average	**59%**			
				Storage Levels [c]	
QLD	Central Highlands	83%	Barker Barambah (mid-Burnett)	3%	
	Dawson Valley	14%	Chinchilla Weir (Darling Downs)	32%	
	Biloela	100%	Dawson Valley	7-73%	
	Darling Downs	76%	Nogoa Mackenzie	15%	
	Dirranbandi	89%	St. George	16%	
	St. George	67%	Upper Condamine	11%	
	Macintyre Valley	64%	Fairburn Dam, Emerald	13%	
	Average	**71%**			

[a] Indicates reduction during the 2006-07 season compared to 2001-02.

[b] Includes water carried over from the 2005-06 season.

[c] Indicates current storage levels of dams and weirs in Queensland (as of January 2007).

Benchmarking water management

The Benchmarking Process

The Australian cotton industry is proactively improving the management of its water resources. In recent years, the industry has invested considerable resources in research and extension programs aimed at improving the cotton produced per unit of water input and protecting water resources, at both the field and watershed scales. It is expected that the industry will continue investing additional resources in the years to come. For instance, according to (Roth, 2006):

"In its first three years, the Cotton CRC, with its partners, is investing $17 million in water research, education and extension so that the Australian cotton industry can remain the world leader in water management."

The industry is also investing in the development of benchmarking processes and tools to be able to measure the impact of those investments. A benchmark can be defined as:

"***A standard by which something can be measured or judged,"*** and benchmarking**,** as ***"To measure (a rival's product) according to specified standards in order to compare it with and improve one's own product"*** (Lexico Publishing Group LLC, 2006).

Thomson and Schofield (1998), however, defined benchmarking as:

"***An on-going systematic process to search for and introduce best practice management into an organisation or industry, structured in such a way that all parts of the organisation and industry understand and achieve their full potential***."

The benchmarking process is intended to help the industry evaluate the impact of its investments in water management programs and to identify priorities for future investments. Benchmarking agricultural water management, however, is a difficult process. A common way of benchmarking agricultural water management is by calculating how much "yield" is produced per unit "water". This seems quite simple, but it can be very ambiguous and misleading since there is not widely accepted national or international standard on how "yield" and "water' are measured and reported. The term "yield" is sometimes measured as "total dry mass" or just as "harvestable yield." For cotton, harvestable yield is either reported as "lint" or "seed" yield. The "water" term could also mean "irrigation", "irrigation + rain", "irrigation + rain + soil water", or "evapotranspiration." The "water" term can either be measured or estimated using techniques with different levels of accuracy, and could be measured at different scales (district, farm gate, or field scale). Additional ambiguities result from the fact that rain in some case can mean "total rain," and in others, "effective rain," and in some cases it is measured on site, and in others it is measured at a weather station located a long distance from the farm, which can make a huge difference. Also, irrigation in some cases means "irrigation applied", and in others, "effective irrigation" or "irrigation infiltrated."

In addition, the ratio "yield/water" is known by different names by different people, even when calculated the same way. Terms in the literature include "*water use efficiency*," "*irrigation water use efficiency*," "*crop water productivity*," etc. In this document, the term water use efficiency (WUE) is used, which in general is the ratio of some measure of output (usually crop yield or $) to some measure of water input. A review of how the WUE concept has evolved through time was given by Fairweather et al. (No date). Thomson (1998), however, suggested that water use efficiency was an incorrect use of the technical term "efficiency", which usually expresses a dimensionless percentage, instead of a ratio of two quantities with different units. He argued that it would be technically incorrect to call the "bales/ML" or "$/ML" an "efficiency" and that the term should, therefore, be avoided in favour of correctly naming "irrigation ratios". Thomson and Schofield (1998) as an overall definition of WUE stated that:

“Water use efficiency includes any measure that reduces the amount of water used per unit of any given activity, consistent with the maintenance or enhancement of water quality and the environment”

Due to the lack of a national or international standard regarding the definition and calculation of water use efficiency, the National Program for Sustainable Irrigation launched a consultation process to develop a national water use efficiency framework to be proposed as a standard for Australia. This process resulted in the definition of a general framework for irrigation performance indicators, which introduced the concept of performance indices as reported by Purcell and Currey (2003). They stated that under the defined framework, water use efficiency (WUE) did not have a specific meaning, but it was to be used as a generic term for a series of more specific irrigation performance indicators referred to as “*water use indices*.” Some of the indices they proposed are defined in Table 6.

Table 6. Definition of water use efficiency indices.

Index	Name	Definition [a]	Units
GPWUI	Gross production water use index	Total product (bales) [b] Total water applied (ML) [c]	bales/ML
IWUI (Applied)	Irrigation water use index	Total product (bales) Irrigation water applied (ML)	bales/ML
CWUI	Crop water use index	Total product (bales) Evapotranspiration (ML)	bales/ML
MIWUI (Applied)	Marginal irrigation water use index	Marginal production due to irrigation (bales) Irrigation water applied (ML)	bales/ML
GPEWUI(Applied)	Gross production economic water use index (Applied)	Gross production ($) Total water applied (ML)	$/ML
IEWUI (Applied)	Irrigation economic water use index	Gross production ($) Irrigation water applied (ML)	$/ML
MIEWUI (Applied)	Marginal economic irrigation water use index	Marginal production due to irrigation ($) Irrigation water applied (ML)	$/ML
CEWUI	Crop economic water use index	Gross production ($) Evapotranspiration (ML)	$/ML
IWUI (Farm Gate)	Irrigation water use index at the farm gate	Total product (bales) Total water supplied at the farm gate (ML)	Bales/ML

[a] These definitions were taken from Purcell and Currey (2003). Here, however, the total product is given in “bales” and all water variables are given in “ML”. In the original source, they used “kg” instead of “bales” and some of the water variables were given in “mm” and others in “ML”.

[b] Variables can also be given in a “per unit area” basis. For instance, Total product can be given in bales/ha, and Total water applied in ML/ha, which will result in the same units of bales/ML for the IWUI (Applied).

[C] Total water applied includes irrigation, water stored in the soil profile at sowing, and effective rainfall.

In this report, cotton yield is expressed in “bales/ha” and “kg/ha” for lint and seed, respectively, and water variables are given in megalitres (ML), to be consistent with what is commonly used in Australia. Most of these indices can be seen as biophysical indices (i.e. CWUI, IWUI (Applied), GPWUI) while those that involve money ($) can be viewed as economic indices (i.e. CEWUI, IEWUI (Applied)…).

Based on this WUE framework, the next steps for benchmarking the Australian cotton industry is the analysis of existing information, and the development of mechanisms and tools for continuous collection and warehousing of WUE data. This report is part of the benchmarking process and reviews the available information on WUE in Australia and in selected areas around the world.

Challenges for effective benchmarking

It has been suggested that the cotton industry has probably gone close to doubling its WUE over the last decade mainly by increasing yield per unit area (bales/ha), and a new challenge to "*double again the WUE by 2015*" has recently been proposed (Dugdale and Pyke, 2006). Some important questions are:

- Where is the industry now in terms of WUE and how does it compare to other water users?
- How is the industry going to know when the WUE has doubled?
- Is the industry measuring what it needs to measure to be able to evaluate WUE?
- Does the industry have the necessary tools and procedures to evaluate WUE?
- Does the industry have a way for capturing, analysing and reporting WUE information?

Currently there is lack of information about the proportion of cotton growers that measure their water use and are able to calculate WUE, although is known that many farmers and crop consultants actually do it. In a recent survey within the cotton industry 57% of growers indicated that they calculated WUE in terms of bales/ML (Figure 11).

Figure 10. Commercial cotton farm in the Darling Downs where water balance data needed to evaluate water use efficiency was being collected by a crop consultant (photo by Jose Payero).

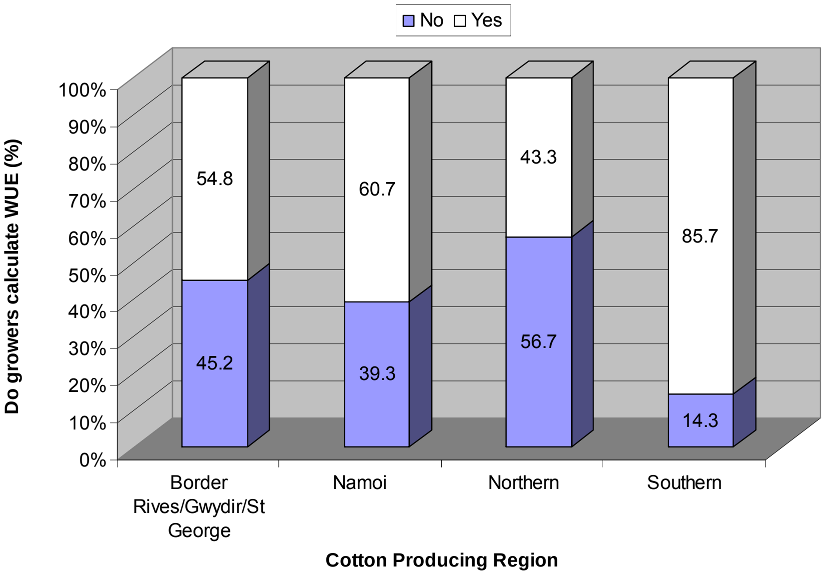


Figure 11. Volume Response to “Do growers calculate water use efficiency (WUE) in terms of bales/ML?” by region for the 2005-06 season. Data was obtained from a survey for cotton producers conducted by Doyle and Coleman (2007).

The WUE Benchmark Objective

The first step towards effective benchmarking is to define what it is that the industry should pursue. A possible, and ambiguous, objective could be to simply “increase or double WUE.” However, in the range in which crop yields respond to additional water, increasing WUE can be achieved in many ways by changing either or both of its components (yield and water) as indicated in Table 7. Again, in this context, the term “water” can mean irrigation, in-crop water inputs (rain + irrigation), water use (evapotranspiration) or total water (rain + irrigation + soil water).

Table 7. Effect of changes in yield and water on water use efficiency

	Water		
Yield	Constant	increase	Decrease
Constant	⇔	⇓	⇑
Increase	⇑	⇑⇔⇓	⇑
Decrease	⇓	⇓	⇑⇔⇓

“⇑”= increase, “⇔” = constant, “⇓’ = decrease, and “⇑⇔⇓” = can increase, stay constant, or increase depending on the relative magnitude of changes in yield and water.

It is important to define how the increase in WUE is going to be accomplished since it can have implications about the need for investing in the development of new technologies (via research projects) or in the application of available ones (via extension projects). Also, how the increase in WUE is going to be achieved could affect the willingness of people to participate in the process. For instance, if increases in WUE are to be achieved by using less water, it then becomes necessary to decide in the early stages of the process what is going to happen with the water that is “saved.” If farmers can keep the water that they save, then they will be more likely to invest in water saving technologies.

Another issue is to clearly define if the objective is to increase a biophysical water use index or an economic one. If the objective is to increase a biophysical water use index, then it is necessary to decide which one of either the CWUI (yield/ET), the GPWUI (yield/total water), or the IWUI (yield/irrigation) will be targeted. This is important because if the objective is to increase CWUI, then it can be done by fully-irrigating (or even by over-irrigating) to obtain the maximum potential yield. Also, since in a fully-irrigated situation the ET component cannot be significantly modified by management, then the strategy should be to increase yield potential by other means like plant breeding, nutrient management, etc. On the other hand, if the objective is to maximize the GPWUI or the IWUI, wasting water by over-irrigating should then be avoided, and strategies to minimize water inputs while increasing or maintaining yields should be applied.

Instead of having the objective of increasing WUE (bales/ML), the industry could have a purely economic objective, such as increasing some measure of economic returns (i.e. profits, net return, gross margins, etc) per unit irrigation ($/ML), per unit area ($/ha), or for the whole farm ($/farm), which could require a different strategy than just increasing the bales/ML. The economic objective to increase economic returns could also involve considering the benefits of growing other crops, or including them in crop rotations with cotton where and when practical. In this respect, English et al. (2002) suggested that given the current water scarcity and environmental concerns that affect irrigated agriculture in many parts of the world, irrigated agriculture will need to adopt a new paradigm based on the economic objective of maximizing net economic benefits rather than the biological objective of maximizing yield per unit area. They, however, warn that irrigation to maximize economic benefits (i.e. profits) was a substantially more complex and challenging problem than just meeting crop water requirements to produce maximum yield, since both biological and economic factors needed to be considered in the analysis. It should then be recognized that water management strategies needed for maximizing profitability ($/ML) (considering environmental sustainability) do not necessarily coincide with those needed for maximizing the bales/ML or bales/ha.

Table 8. Economic comparison of cotton and grain crops during 2006 for “cool” and “hot” cotton producing areas in Australia (Wylie, 2006).

		Sorghum		Corn	Wheat	Cotton	
Variable	Units	Cool	Hot	Cool	High Input	Cool	Hot
Yield (t/ha)	(t or bales/ha)	11	8.75	12.0	9.0	8.75	9.37
Irrigation (ML/ha)	(ML/ha)	3.0	4.0	3.5	2.8	4.0	6.0
Farm Price ($/t or bale)	($/t or bale)	$225	$225	$235	$255	$420	$420
Gross Return	($/ha)	$2475	$1968	$2820	$2295	$3675	$3937
Gross Margin	($/ha)	$1617	$1042	$1796	$1319	$1812	$1530
Profit	($/ha)	$1252	$677	$1431	$954	$1320	$800
Profit	($/ML irrigation)	$417	$170	$409	$340	$330	$133
Rotation benefit to cotton	($/ML irrigation)	$122	$98	$104	$132		

In 2006, due to a combination of high grain prices and low cotton prices, an economic analysis in the cotton producing areas conducted by Wylie (2006) showed that profit per unit irrigation ($/ML) was higher for grain crops (sorghum, maize, and wheat) compared to cotton, especially under cool growing environments (Table 8). He also showed considerable economic benefits of including grain crops in rotation with cotton. The high grain prices were mainly due to increased demand for grains to be used in ethanol production. Also, Thomson and Schofield (1998), based on ABS statistics for 1992-96 and other sources, estimated the gross returns per unit irrigation for some of the key irrigation industries in Australia as: Horticulture ($1400/ML), Sugar ($960/ML), Cotton ($360/ML), Rice ($160/ML), and Pasture ($100/ML). Of course, as attractive as other enterprises may seem from the economic standpoint, for a variety of reasons not all farmers have the flexibility or the desire to totally change enterprises or include other crops in rotation with cotton. Also, agricultural enterprises require specific environments, technology, infrastructure, markets, and culture, and therefore they cannot be easily interchanged.

The IWUI

Another challenge for effective benchmarking is the need to use the appropriate index based on a clearly stated objective. If the objective is to compare performance across regions and seasons, indices that allow these comparisons need to be selected. For example, a common approach for benchmarking is to use indices that are based on irrigation water applied such as the IWUI(Applied). This index, however, has the shortcoming that it can vary significantly for different regions and seasons since there is not unique relationship between crop yield and irrigation applied as illustrated in Figure 12 for cotton at Emerald. The relationship varies with season depending on in-crop rainfall and other factors, and the data for the 1983-84 season shows that during wet years, irrigation may not be needed and could even decrease yields. Figure 12 shows the typical curvilinear response functions often reported for situations in which irrigation applied ranged from deficit-irrigation to over-irrigation. The curvilinear response to irrigation results from application of excess water, some of which could be lost by runoff, deep percolation and evaporation, and some could just stay unused in the soil profile after the crop is harvested. The curvilinear response could also result from yield reduction by excess water due to factors like nutrient leaching or waterlogging. In should be kept in mind, however, that over-irrigation is actually desirable in situations in which a leaching fraction needs to be applied to prevent salt build-up in the soil profile. Also, over-irrigation can sometimes occur even with good water management due to the stochastic nature of rainfall. In situations in which the crop is not over-irrigated, water is not wasted by low irrigation efficiencies, and irrigations are properly scheduled, crop yield increases approximately linearly with irrigation.

In most agricultural regions and seasons, the yield response to irrigation usually has a positive intercept, that is, there is usually some yield (dryland yield) even with no irrigation due to in-crop rainfall and water stored in the soil profile at sowing. In arid regions, however, the dryland yield could be zero and, in some very dry areas and seasons it may even take a considerable amount of irrigation before a marketable yield can be obtained. Gibb (1995) reported minimum and maximum simulated cotton yields expected 8 years out of 10 as a function of irrigation applied for different cotton producing towns in Australia. The minimum values would likely correspond to dry seasons, the maximum values to wet seasons, and the average of both would approximate a “normal” or average season (Table 9).

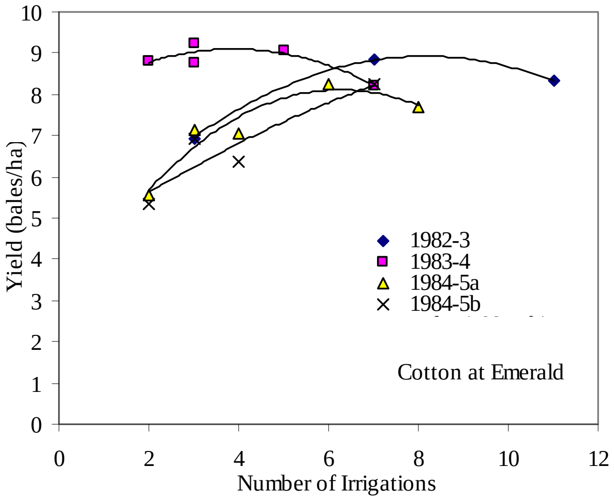


Figure 12. Cotton lint yield as a function of number of irrigations obtained at Emerald during three seasons. Adapted from data reported by Keefer (No date).

Table 9. Simulated cotton yield expected 8 out of 10 years as a function of irrigation applied for dry, wet, and average seasons in different cotton producing towns in Australia. Adapted from data reported by Gibb (1995)

Season	Irrigation (ML/ha)	Biloela	Bourke	Breeza	Brookstead	Collarenebri	Dalby	Emerald	Goondiwindi	Gunnedah	Hillston	Moree	St. George	Warren	Wee Waa
Dry Season	2	1.2	1.42	0.75	1.2	1.32	1.57	1.84	1.41	1.24	0.39	1.4	1.84	0.68	1.26
	3	2.65	2.03	1.23	1.98	2.14	2.13	3.26	2.45	1.84	1.07	1.89	2.03	1.33	2.02
	4	6.03	2.72	2.24	3.12	3.35	3.76	4.3	3.39	2.89	2.02	3.32	3.27	2.64	3.55
	5	6.88	4.39	3.44	4.8	5.22	6.59	5.86	5.61	5.47	3.64	5.36	4.37	4.94	5.38
	6	7.31	5.63	3.44	5.86	6.9	7.25	6.25	6.72	7.13	4.86	6.77	5.16	6.22	7.11
	7	7.56	5.75	3.44	5.86	7.28	7.25	6.25	7.02	7.31	5.6	7.02	5.16	6.76	7.31
Wet Season	2	5.93	5.11	4.01	5.92	5.12	7.34	6.92	6.08	5.67	2.16	5.59	5.48	4.22	5.98
	3	7.59	6.2	6.01	7.2	6.53	7.79	7.87	7.48	7.57	3.34	7.21	6.48	5.96	7.25
	4	9.19	7.81	6.84	7.9	7.72	8.68	8.72	8.61	8.8	4.79	8.27	7.89	7.61	8.47
	5	9.27	8.48	7.9	8.29	8.93	9.17	9.04	9.18	9.17	6.94	8.8	8.04	8.15	9.05
	6	9.29	9.22	8.61	9.19	9.77	9.69	9.08	9.45	9.64	8.51	9.71	8.79	9.13	9.58
	7	10.2	9.47	8.69	9.56	9.78	9.74	9.27	9.64	9.93	8.6	9.72	9.44	9.63	9.8
Average	2	3.57	3.27	2.38	3.56	3.22	4.46	4.38	3.75	3.46	1.28	3.50	3.66	2.45	3.62
	3	5.12	4.12	3.62	4.59	4.34	4.96	5.57	4.97	4.71	2.21	4.55	4.26	3.65	4.64
	4	7.61	5.27	4.54	5.51	5.54	6.22	6.51	6.00	5.85	3.41	5.80	5.58	5.13	6.01
	5	8.08	6.44	5.67	6.55	7.08	7.88	7.45	7.40	7.32	5.29	7.08	6.21	6.55	7.22
	6	8.30	7.43	6.03	7.53	8.34	8.47	7.67	8.09	8.39	6.69	8.24	6.98	7.68	8.35
	7	8.88	7.61	6.07	7.71	8.53	8.50	7.76	8.33	8.62	7.10	8.37	7.30	8.20	8.56

The simulated yield versus irrigation response functions for dry, normal, and wet years for Wee Waa, Australia, are shown in Fig. 13. As expected, the curvilinear functions in Figure 13A fit the data better than the linear functions in Fig. 13B, however, the linear functions fit the data quite well, specially when the crop is not over-irrigated. Figure 13B shows a positive dryland yield for wet and normal years, but during dry years, the intercept of the line is negative, therefore, from the equation of the line it can be shown that it would take more than 1.22 ML/ha of irrigation to obtain the first yield increment in an average dry year.

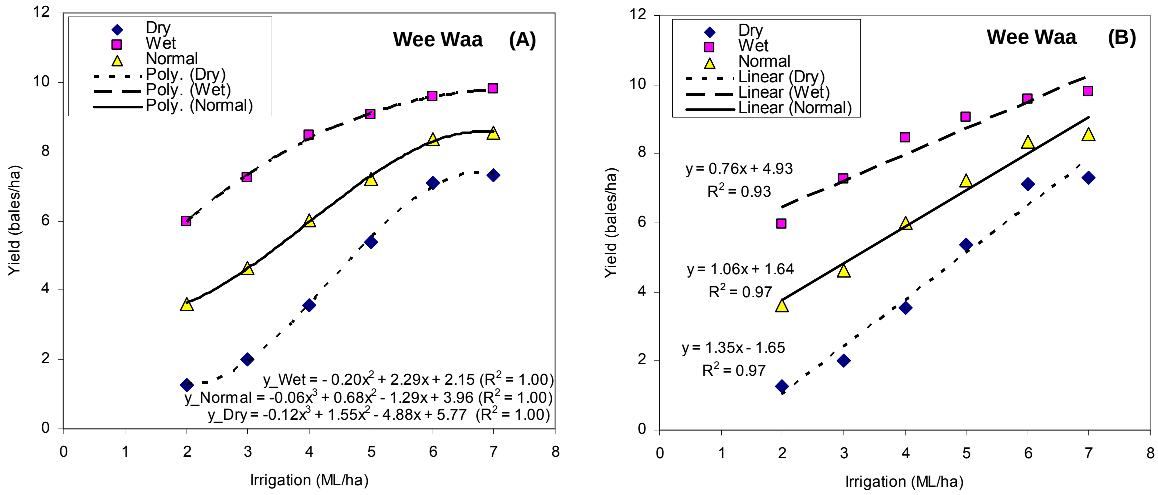


Figure 13. Simulated cotton yield expected 8 years out of 10 as a function of irrigation applied for dry, normal, and wet years at Wee Waa, Australia, adapted from data reported by Gibb (1995). (A) polynomial fit and, (B) linear fit.

Regardless of how good or bad water management is, the sign (positive, negative, or zero) of the dryland yield that can be obtained in a given location and season is what will determine if the IWUI increases, stay constant, or decreases with additional irrigation. Figures 13A and 13B show considerable variation in dryland yield (yield when irrigation = 0) from season and location. Assuming that the yield versus irrigation response function is approximately linear when no over-irrigation is applied, in areas and seasons with a positive dryland yield, the yield versus irrigation response function and IWUI can be approximated as:

$$Yield = a(Irrigation) + dryland\ yield \qquad (1)$$

$$IWUI = yield/Irrigation = a + (dryland\ yield/Irrigation) \qquad (2)$$

where "a" and "dryland yield" are the slope and intercept of the line, respectively. Equation 2 implies that in this situation, IWUI decreases with increasing irrigation and the relationship is curvilinear, as indicated in Fig.14 (Wanjura et al., 2002).

This implies that in areas (and seasons) where a positive dryland yield is obtained, IWUI is maximised with the first irrigation increment, decreasing thereafter as more irrigation is applied. Therefore, if water is limited and the purpose is to maximise IWUI, it is preferable to deficit-irrigate a larger area than fully-irrigate a smaller area. This strategy, however, although increases IWUI does not necessarily increases economic return and profit.

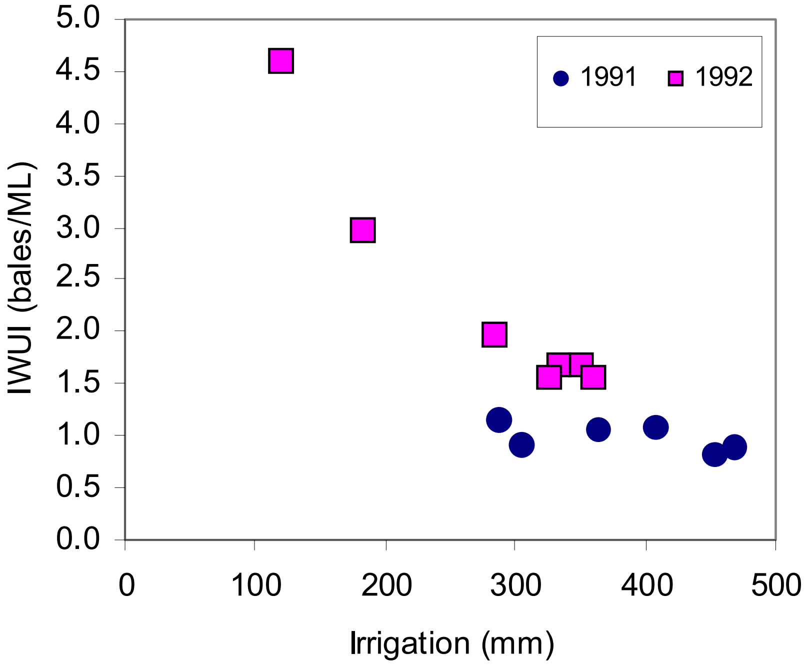


Figure 14. Response of cotton irrigation water use index (IWUI = lint yield/irrigation) to irrigation during the 1991 and 1992 seasons at Lubbock, Texas, USA. Adapted from data reported in Table 2 of Wanjura et al. (2002).

However, in arid environments, the intercept of the line (dryland yield) could be exactly zero (a rare coincidence), or even negative. A negative dryland yield does not have a physical meaning, but indicates that it would take some amount of irrigation to obtain the first increment in measurable yield. If the intercept (dryland yield) of equation 2 is exactly zero, then the relationship between IWUI and irrigation becomes:

$$IWUI = yield/Irrigation = a \qquad (3)$$

In other words, IWUI is constant with irrigation, and it is equal to the slope of the yield versus irrigation response function.

This implies that in areas (and seasons) where the intercept of the yield versus irrigation response function is exactly zero, the IWUI would be constant with irrigation (if irrigation efficiency = 100%). Therefore, if water is limited and the purpose is to maximise IWUI, the same IWUI is obtained by either deficit-irrigating a larger area or fully-irrigating a smaller area. This situation, however, would be extremely rare.

On the other hand, if the intercept of the yield versus irrigation response function is negative, then equation 2 becomes:

$$IWUI = yield/Irrigation = a - (dryland\ yield/Irrigation) \qquad (4)$$

In this case, then IWUI will increase with irrigation, and the increase should be curvilinear.

This implies that in areas (and seasons) where the intercept of the yield versus irrigation response function is negative, maximising IWUI requires full irrigation. Therefore, if water is limited and the purpose is to maximise IWUI, it is preferable to fully-irrigate a smaller area than deficit-irrigate a larger area. This strategy, however, although increases IWUI does not necessarily increases economic return and profit.

Figure 15 shows the simulated IWUI values as a function of irrigation applied for dry, normal, and wet years at Wee Waa, Australia (adapted from data reported by Gibb (1995)). It shows that for wet years, when a high dryland yield can be obtained, the IWUI rapidly decreases with irrigation. In a normal year, when the dryland year is still positive but relative small compared to the wet year, the IWUI still decreases with irrigation, but at a smaller rate, and will tend to be constant as the dryland yield approximates zero. For the dry year, on the other hand, when no dryland yield can be obtained, the IWUI increases with irrigation.

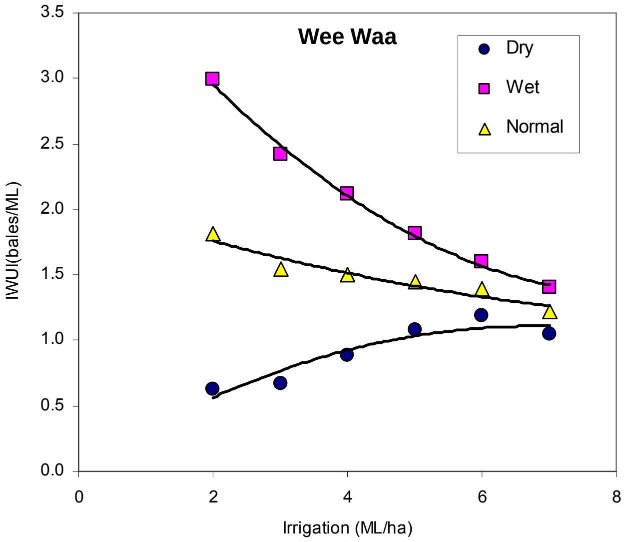


Figure 15. Simulated cotton irrigation water use index (IWUI = lint yield/irrigation) expected 8 out of 10 years as a function of irrigation applied for dry, normal, and wet years at Wee Waa, Australia, adapted from data reported by Gibb (1995).

Since irrigation water requirements can vary significantly by region and season, the calculated IWUI that can be achieved can also vary widely and therefore it is of limited usefulness for comparison among regions and seasons. Figure 16 shows how the IWUI for cotton varied during four seasons at Narrabri, depending on in-season rain. For the 1983/84 wet season when the in-season rain was 506 mm, the irrigation water requirements were very low and the IWUI was extremely high (8.02 bales/ML). For the next three seasons, it was much lower (1.61, 1.86, and 1.55 bales/ML), which does not necessarily reflects a change in water management. Figure 16 also shows that the CWUI, which is based on evapotranspiration instead of irrigation water applied, was much more consistent from season to season. Therefore, these results suggest that when evapotranspiration data are available, the CWUI would be a more appropriate index for comparison among regions and seasons than the IWUI.

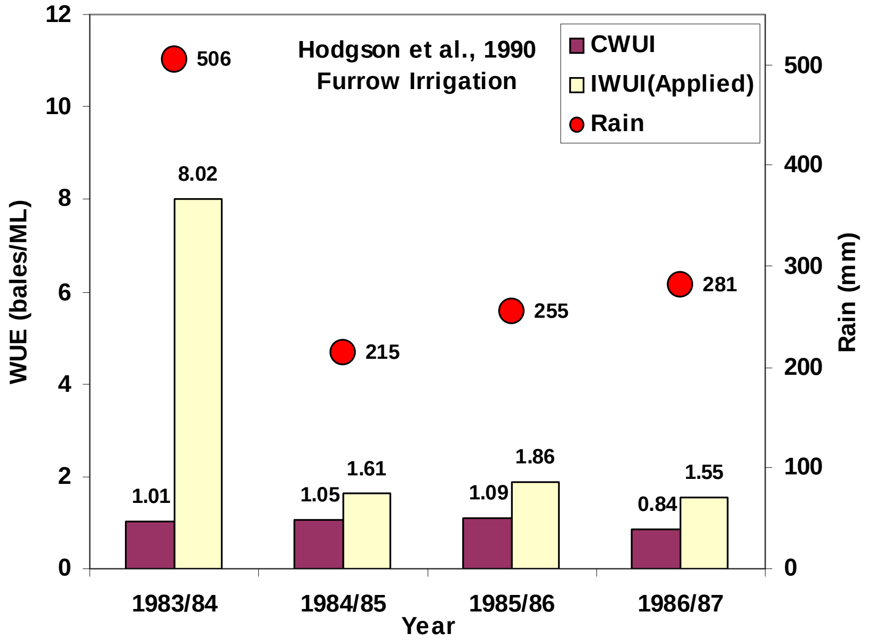


Figure 16. Crop water use index (CWUI = Lint yield/Evapotranspiration) and Irrigation water use index (IWUI = Lint yield/Irrigation) for furrow-irrigated cotton obtained during four seasons at Narrabri, Australia. Adapted from values reported in Table 1 of Hodgson et al. (1990).

The CWUI

The consistency of the CWUI results from the observation that for most commercial crops, including cotton (lint and seed), harvestable yields have been shown to increase almost linearly with crop evapotranspiration, and the intercept of the line is always negative. Figure 17 shows the relationship between cotton lint yield and evapotranspiration at Narrabri, Australia, obtained from data reported by Cull et al. (1981). In this study, crop stress, as indicated by reduced evapotranspiration also linearly increased micronaire, which is an indication of reduction in lint quality. The seasonal evapotranspiration (ET) in this study, however, could have some errors since it was estimated from neutron prove soil water content measurements. It is odd that the yield versus ET response function when extrapolated to intercept the “X” axis indicates that more than 500 mm of ET would be required to produce no yield, which is unusually high. Despite this shortcoming, the linear shape of the relationship between yield and ET is consistent with results obtained by other researchers, although the slope of the line is steeper than expected. Overestimation of ET in this study could be due to underestimation of the deep percolation component when using a water balance approach to estimate ET as a residual.

Linear (or almost linear) yield versus ET response functions for cotton, have been reported for other areas, including Texas (Howell et al., 2004), California (Howell et al., 1984), California and New Mexico (Sammis, 1981), Spain [for seed] (Mateos et al., 1991; Orgaz et al., 1992), India [for seed] (Jalota et al., 2006), among others.

Since the CWUI does not account for differences in ET requirements among regions to produce the same yield, it also has some limitations as a benchmarking tool.

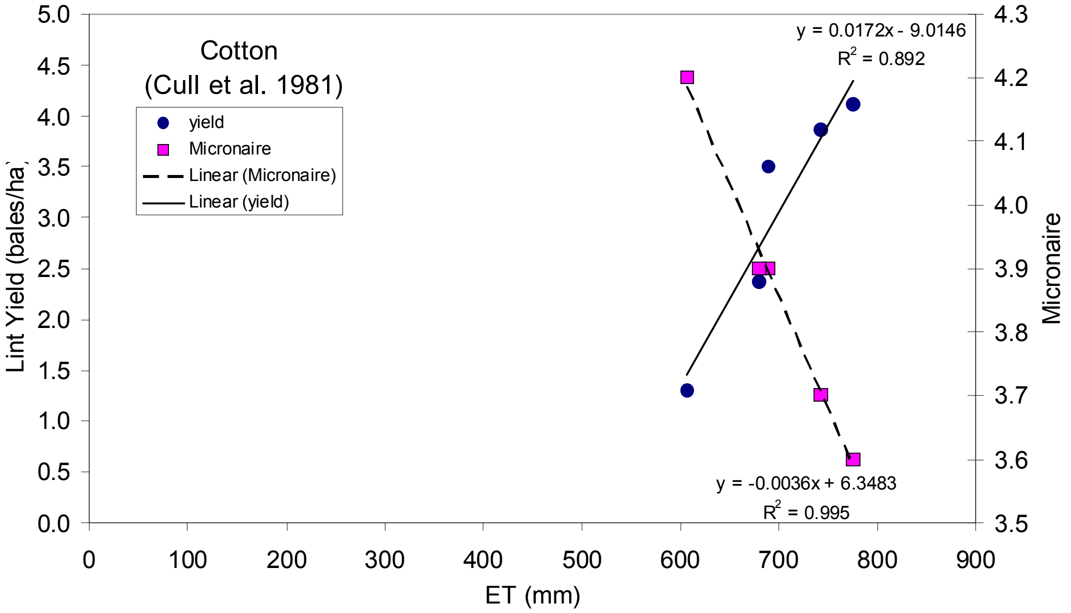


Figure 17. Cotton lint yield and fibre micronaire as a function of evapotranspiration (ET) obtained from data reported by Cull et al. (1981) for the 1976/77 season at Narrabri, Australia.

Doorenbos and Kassam (1979a), Jensen (1968), and others, have also suggested that the yield versus ET response function for a crop is affected by stress timing, with certain stages of growth being more sensitive to water stress than others. The more sensitive stages are usually related to the reproductive stages when, coincidentally, the crop has a high ET demand. Stressing the crop during periods of high ET demand implies a high reduction in ET, which is associated with the observed high reduction in yield during the reproductive stages. The question of the effect of stress timing on the yield versus ET relationship for a particular crop is an interesting one, which still deserve further research to be answered satisfactorily. Stress timing has been suggested to be particularly important in cotton, since timing of water stress has been shown to affect plant growth, boll retention, yield, and fibre quality (Gibb, 1995; Hearn, 1994).

Doorenbos and Kassam (1979b) proposed that the effect of both the severity and timing of water stress on crop yield (including cotton) could be quantified using the linear model:

$$(1 - Y_a/Y_m) = ky(1 - ET_a/ET_m) \quad (5)$$

where Y_a = actual yield (bales ha^{-1} or kg ha^{-1}), Y_m = maximum yield (bales ha^{-1} or kg ha^{-1}), ET_a = actual evapotranspiration (mm or ML ha^{-1}), ET_m = maximum evapotranspiration (mm or ML ha^{-1}), and *ky* = empirical crop yield response factor that varies depending on the growth stage when water stress occurs (unitless). A relatively high *ky* value during a given growth stage indicates that stress during that stage causes a relatively high yield reduction. Another mathematical model to explain the effect of severity and timing of water stress on crop yield, which also uses an empirical factor similar to *ky* to account for stress timing was previously proposed by Jensen (1968). However, although these models were proposed decades ago, defining consistent *ky* values for different crops and growth stages has been challenging and very variable values have been reported, as indicated in Table 10 for cotton. Moutonnet (2002) found that *ky* values obtained from two different datasets varied widely from 0.20 to 1.15 and from 0.08 to 1.75, respectively.

Table 10. Published crop yield response factors (ky) for cotton.

Ky	Respective growth stages	Reference
0.2, 0.5, 0.25	Vegetative, flowering, ripening	Doorenbos and Kassam (1979b)
0.99	Flowering and yield formation	Kirda (2002)
0.75, 0.48	Bud formation, flowering	Kirda (2002)
0.86	Whole season	Kirda (2002)
0.46, 0.67, 0.88	Boll formation, flowering, vegetation	Kirda (2002)
0.86, 0.48 #	Whole season, boll formation and flowering	Kirda (2002)
1.02, 0.75, 0.48 (Argentina)*	Whole season, initial, crop development	Moutonnet (2002)
0.71, 0.80, 0.60, 0.05 (Pakistan)*	Whole season, initial, crop development, mid season	Moutonnet (2002)
0.99, 0.76 (Turkey) *	Whole season, crop development	Moutonnet (2002)

Values for a planned evapotranspiration deficit of 25%.

* In these studies, treatments were named Tr_0000, Tr_0111, Tr_1011, and Tr_1101 representing irrigation treatments stressed at either of four growth stages (0 = stressed, 1 = no stressed). The growth stages were: (a) initial (0-10% cover), (b) crop development (10% cover to full cover and initiation of flowering), (c) mid-season (effective cover to onset of maturity, and (d) late season (onset of maturity to harvest).

Assuming that yield increases linearly with ET and that some ET is required even when no yield is produced implies that the yield and CWUI versus ET response functions for a given crop and location can be represented by the following equations:

$$Yield = a(ET)-b \qquad (6)$$

$$CWUI = yield/ET = a - (b/ET) \qquad (7)$$

where “a” and “b” are empirical factors representing the slope and intercept of the yield versus ET response function, respectively. Equation 7 implies that CWUI increases with increasing ET and that the relationship is curvilinear. A plot of equation 7 using the yield versus ET functions for cotton given by Jalota et al. (2006) is shown in Figure 18. Although Figure 18 is based on simulation data, the increasing nature of CWUI with ET has also been obtained experimentally for cotton as indicated in Figures 19 and 20 for Australia and Texas, respectively; and for other crops and locations (Huang et al., 2004; Kar et al., 2007; Payero et al., 2005; Payero et al., 2006). Figures 19 and 20 suggest that in situations where water is limited, it is not possible, or even desirable, to achieve the maximum CWUI. Therefore, for a given region, theoretical or empirical CWUI versus ET functions can be defined, which can then serve as a standard to measure irrigation performance. For instance, if a farmer only has water to be able to meet only a given fraction of ET, then they cannot be expected to obtain as high a CWUI as other farmers in the same region that have more water available. Therefore, their performance should be measured against what can be achieved with the available water. For instance, if a farmer has water to only meet 50% of the ET requirements of the crop, what yield should they be getting? To answer this question, yield versus ET functions for the different regions and procedures to calculate ET under deficit-irrigation conditions should be known and easily available. The widespread adoption of scheduling tools like HydroLOGIC could be very valuable for this purpose.

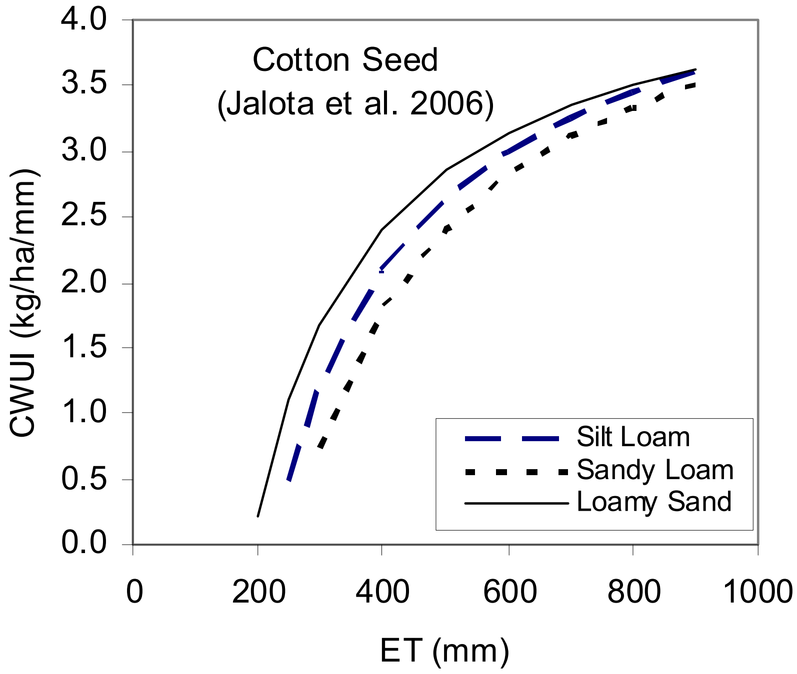


Figure 18. Simulated crop water use index (CWUI= seed yield/ET) as a function of evapotranspiration (ET) obtained for three soil types in India. CWUI values were calculated from equations 2a-2c of Jalota et al. (2006).

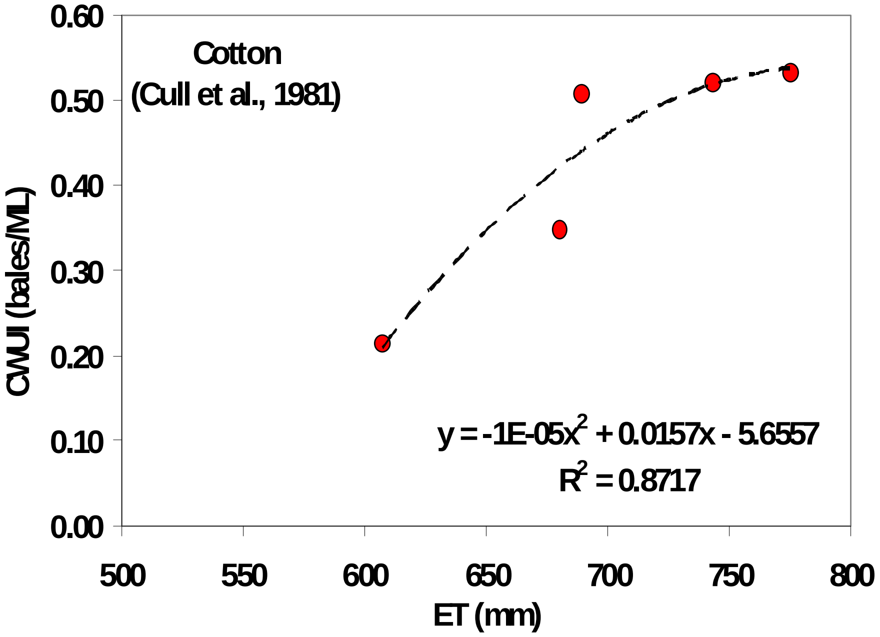


Figure19. Relationship between cotton crop water use index (CWUI= lint yield/evapotranspiration [ET]) obtained from data reported by Cull et al. (1981) for Narrabri, Australia.

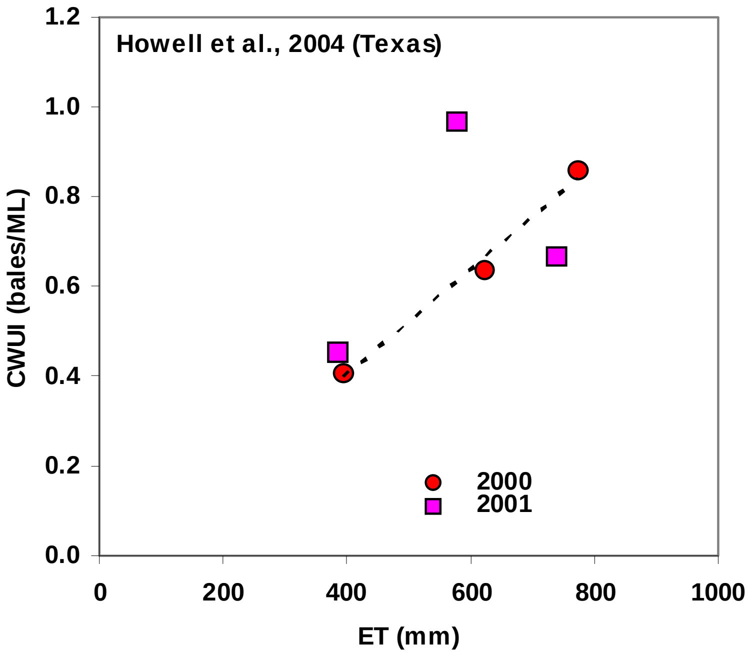


Figure 20. Cotton crop water use index (CWUI= lint yield/evapotranspiration [ET]) as a function of ET for two seasons in Texas. Adapted from data in Table 4 of Howell et al. (2004). ET in this study was measured with weighing lysimeters.

This implies that maximising CWUI requires full irrigation. Therefore, if water is limited and the purpose is to maximise CWUI, it is preferable to fully-irrigate a smaller area than deficit-irrigate a larger area. This strategy, however, although increases CWUI does not necessarily increases economic return and profit.

However, there is disagreement and lack of consistency in the literature regarding the effect of deficit irrigation on the CWUI of cotton. For instance, both increasing and decreasing pattern of CWUI values with increasing crop stress have been reported in Texas and Spain (Figures 21 and 22). When experimental data show that CWUI decreases with increasing ET, close examination of the data often reveals that a plot of yield versus ET will result in a positive intercept of the line, suggesting that some yield can be achieved for ET= 0, which is not possible. These results could be due to inaccuracies in measuring or estimating ET. Lower CWUI for higher ET can also be due to other factors limiting yields of the treatments receiving more water, like waterlogging, nutrient leaching, etc.

The increasing pattern of the CWUI versus ET function, however, does not necessarily mean that areas with high ET demand will have a higher yield potential than areas with lower ET demands. It only applies to a given area when comparing deficit to full irrigation. The information above suggests that CWUI is maximized when crop ET requirements are met.

It was previously stated that the CWUI would be sensitive to the fact that ET demands vary with location and season depending on weather conditions. Figure 23 shows the estimated seasonal ET demands for the cotton producing areas in Australia (Tennakoon and Milroy, 2003). It shows considerable differences in ET demands for the different regions, ranging from approximately 667 mm in the Darling Downs to 797 mm in the Macquarie Valley, a difference of 130 mm. If similar yields are produces in both areas, then the CWUI would be higher in the Darling Downs than in the Macquarie Valley, which is not an indication of the relative ability of irrigators to properly manage water.

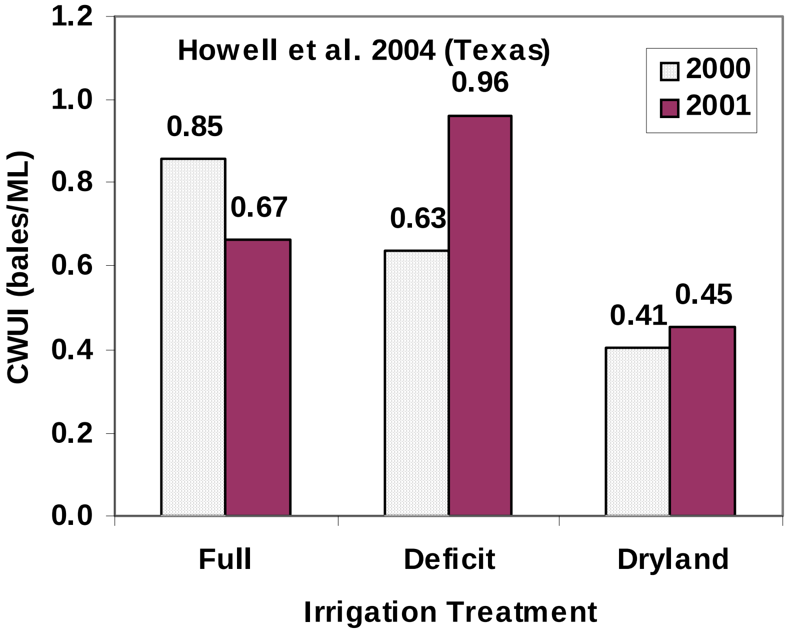


Figure 21. Cotton crop water use index (CWUI= lint yield/evapotranspiration) obtained in Texas for three irrigation treatments. Adapted from data in Table 4 of Howell et al. (2004).

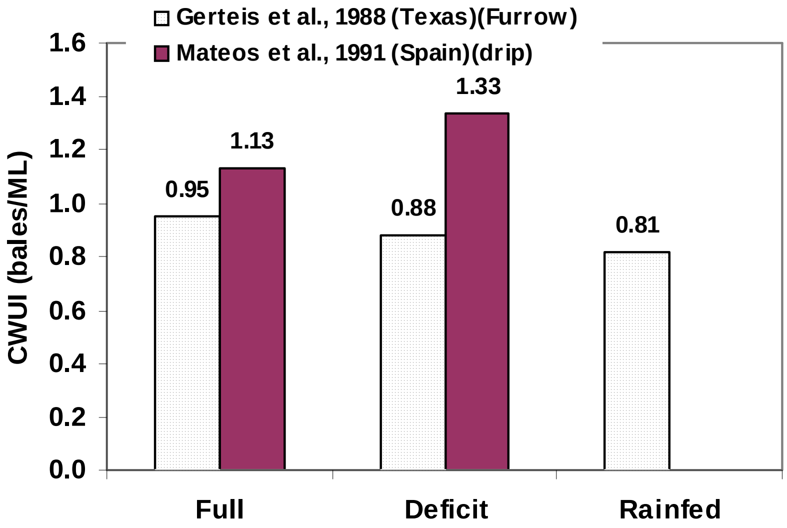


Figure 22. Cotton crop water use index (CWUI=Lint yield/Evapotranspiration) reported for three water regimes. Adapted from values reported in Table 4 of Hearn (1994).

For a given area, considerable differences in ET can result from seasonal differences in weather conditions. Crop ET can also vary considerably with soil water availability, which can be affected by rainfall and by crop management factors such as irrigation, tillage, crop rotation, etc. For instance, considerable differences in cotton ET due to the effect of cropping systems (rotation and tillage) and season have been measured at Narrabri, Australia, in an experiment conducted since 1993 (Figure 24) (Tennakoon, 2000; Tennakoon and Hulugalle, 2006; Tennakoon et al., 1998). These differences would also affect CWUI, limiting comparisons among seasons and cropping systems.

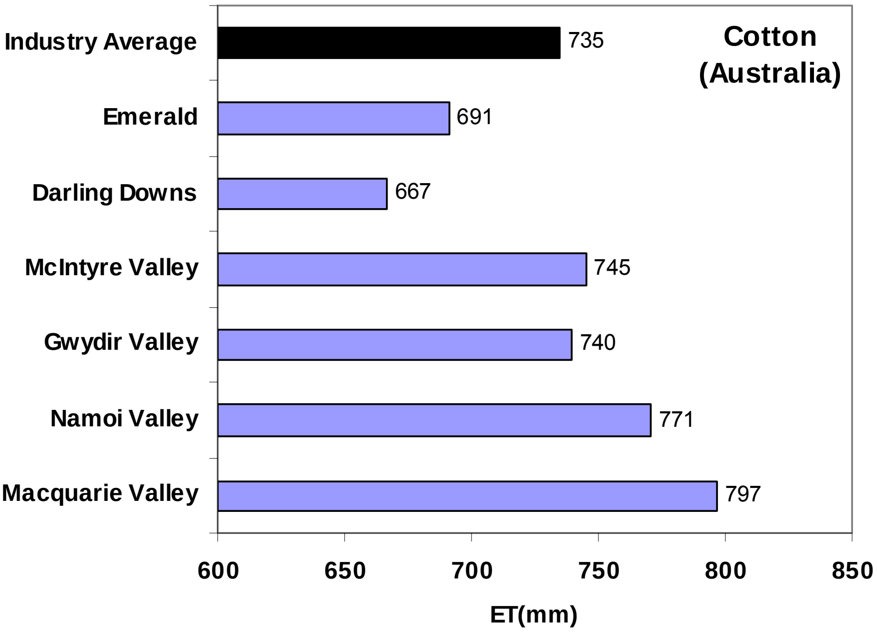


Figure 23. Evapotranspiration (ET) in the different cotton producing valleys in Queensland and New South Wales, Australia. Adapted from average values reported in Table 3 of Tennakoon and Milroy (2003)

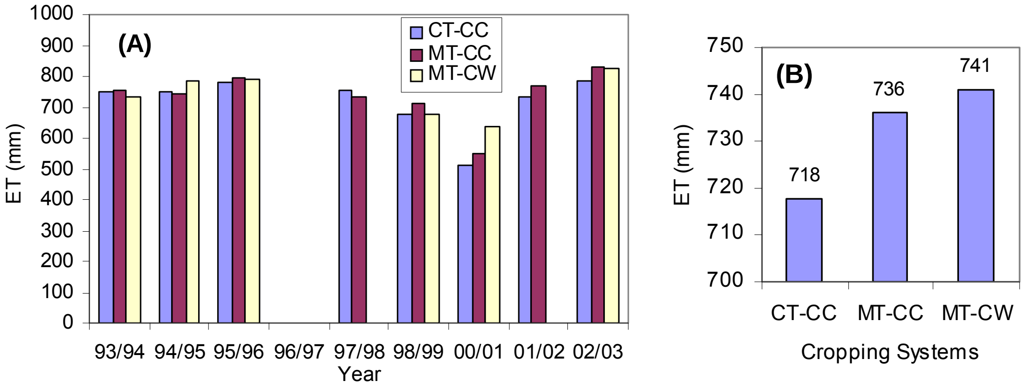


Figure 24. Cotton evapotranspiration (ET) from long-term cropping systems experiment at Narrabri, Australia. Adapted from data reported by Tennakoon (2000), Tennakoon and Hulugalle (2006), and Tennakoon et al. (1998). CT = conventional tillage, MT = minimum tillage, CC = continuous cotton, CW = cotton-wheat rotation. (A) Yearly averages, (B) Averages including all years.

Another significant limitation of the CWUI is that it is possible to obtain high CWUI by over-irrigating the crop. Over-irrigation could maximize yields in situations where yield is not reduced by waterlogging or significant nutrient leaching, which is possible with drip or sprinkler irrigation systems, or with surface irrigation in coarse and medium-textured soils. Since seasonal ET has an upper limit, additional irrigation in excess of the ET requirements of the crop do not necessarily result in significant increases in ET, although some increase could result from additional evaporation. Therefore, over-irrigation could result in high CWUI values, which are not indicative of good performance if the objective is to conserve water resources.

The GPWUI

The behaviour of the GPWUI (yield/total water) with increasing “total water” depends on what is included in the “total water” component. As stated above, total water is commonly referred to as “rain + irrigation,” “effective rain + irrigation” or “rain +irrigation + soil water.” Depending on how “total water” is quantified, the GPWUI can behave as either the IWUI or as the CWUI. If total water is quantified as total water used by the crop, then it will approximate ET and, therefore, the GPWUI will behave like the CWUI. This is only true up to the point at which the crop water requirements are met. After that point, if more water is added, total water will increase while ET will not increase significantly. Therefore, if the crop is over-irrigated, total water will not approximate ET. If total water does not approximate ET, then the GPWUI will behave similarly to the IWUI.

In addition to ET, effective rainfall is the other important factor that determines how much irrigation is needed to grow a crop in a given region. Figure 25 shows the crop water requirements (ET), effective rainfall, and net irrigation requirements (ET - effective rainfall) for selected cotton producing areas around the world (Chapagain et al., 2005). It shows considerable variability in net irrigation requirements for cotton among countries, ranging from as low as 65 mm for Brazil to as high as 1275 mm for Syria. According to this source, the estimated average net irrigation requirement for the Australian cotton industry is 579 mm (5.79 ML/ha). Figure 25 also shows that in places like Argentina with a relative high crop water requirement (877 mm), the net irrigation requirement is quite low (263 mm or 2.63 ML/ha) due to considerable rainfall (615 mm). This discussion suggests that an index to measure irrigation performance should, therefore, be based on net irrigation requirement rather than irrigation, evapotranspiration, or total water.

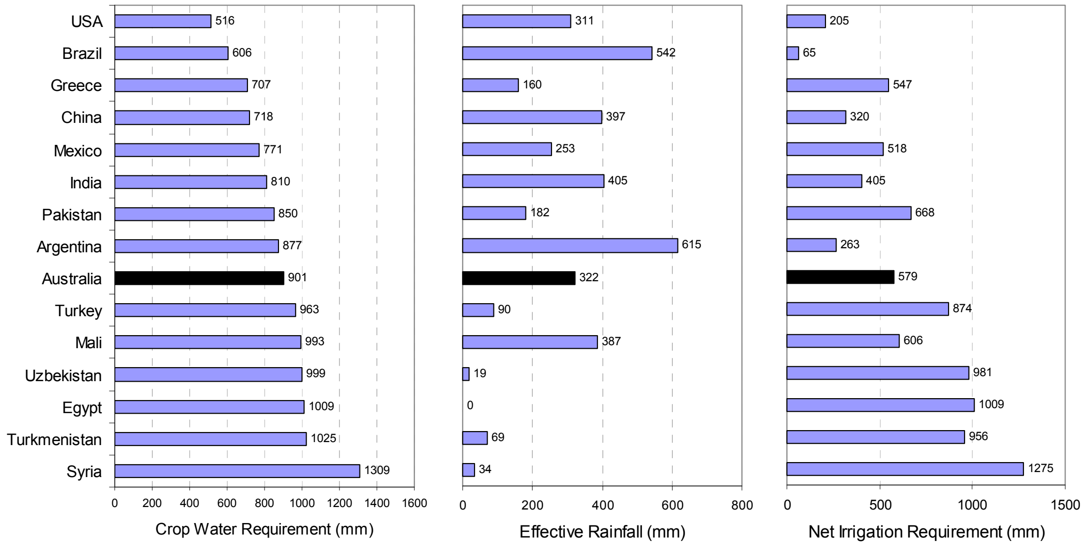


Figure 25. Crop water requirement (evapotranspiration), effective rainfall, and net irrigation requirement at field level for cotton production in the major cotton producing countries. Adapted from data in Table 3.3 of Chapagain et al. (2005).

Regional and Seasonal Differences

Another challenge to effective benchmarking is the differences in yield potential among locations and seasons. These differences could arise from yield limiting factors due to weather conditions (high temperatures, hail, cool shock), soils (salinity, waterlogging), crop health and management (varieties, row configuration, tillage, insects, diseases, irrigation system, etc). For example, figure 26 shows the impact of soil salinity, irrigation system, and water supply (indicated as fraction of ET) on GPWUI (lint yield/total water) for cotton in India (Rajak et al., 2006). In general, in this study soil salinity significantly affected yield potential and consequently decreased the GPWUI, which highlight the importance of maintaining and adequate salt balance in the soil profile. Properly leaching salts with irrigation is especially important in arid areas, when irrigating with low-quality water, and when using highly efficient irrigation systems such as drip and sprinkler systems (Biswas et al., 2005). As expected, higher GPWUI were obtained with drip compared to furrow, and the GPWUI increased with fraction of ET, peaking at a value of fraction of ET of 1.2, and decreasing after that as a result of over-irrigation. However, the GPWUI should have peaked at a value of fraction of ET of 1.0 instead of 1.2, which may indicate errors in the measurement or estimation of fraction of ET.

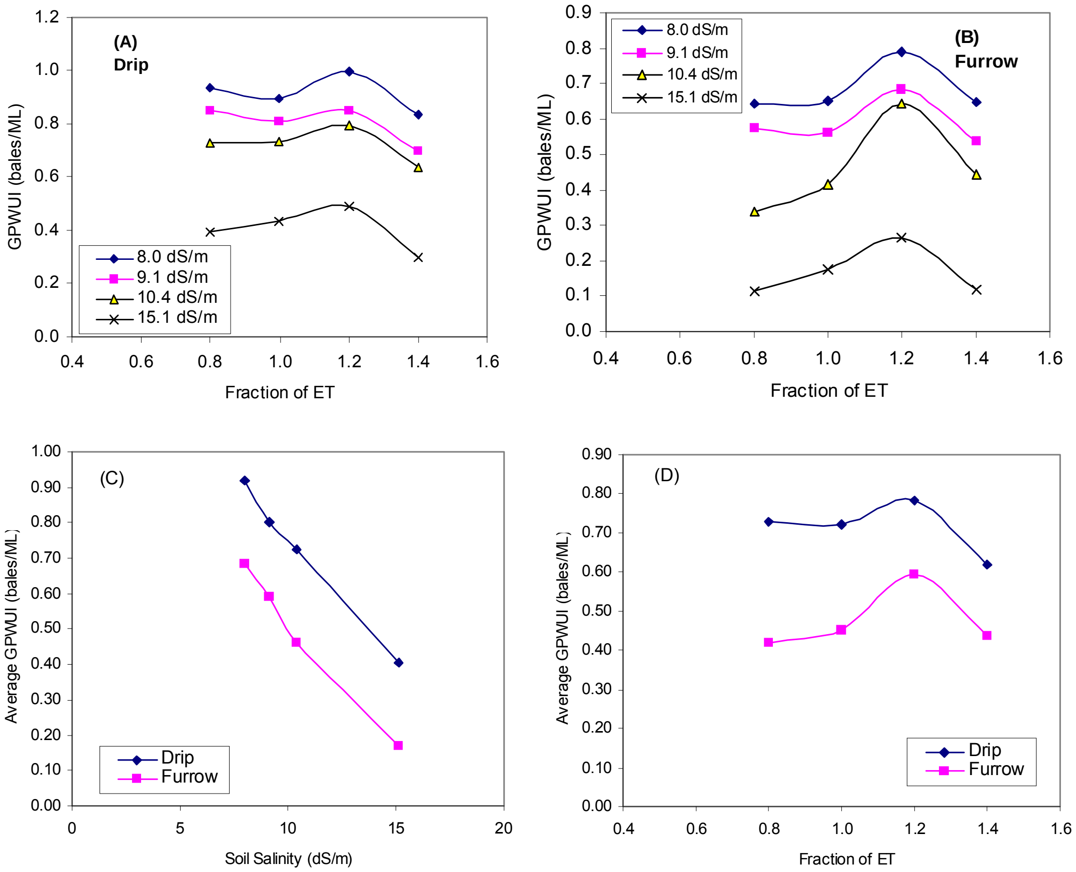


Figure 26. Effect of irrigation system, soil salinity, and water supply (fraction of ET) on gross production water use index (lint yield/total water [irrigation + effective rain]) for cotton obtained in India by Rajak et al. (2006). Fraction of ET = (irrigation + effective rain)/(crop ET).

Figure 27 shows average cotton lint yields reported by Tennakoon and Milroy (2003) for the different cotton producing areas in Australia. It shows considerable yield differences among regions, ranging from 7.45 bales/ha in the McIntyre Valley to 9.83 bales/ha in the Macquarie valley. These yield differences could either be real or they could result from inaccuracies in data collection. If these differences are real, a good understanding of whether they are due to differences in management or to differences in yield potential among locations is needed. If real differences in yield potential exist among regions, then they should be considered during benchmarking. These differences could be accounted for by calculating an appropriate WUE index. It also could be done by establishing a regional WUE target and then reporting WUE values as a percentage of the target regional WUE value.

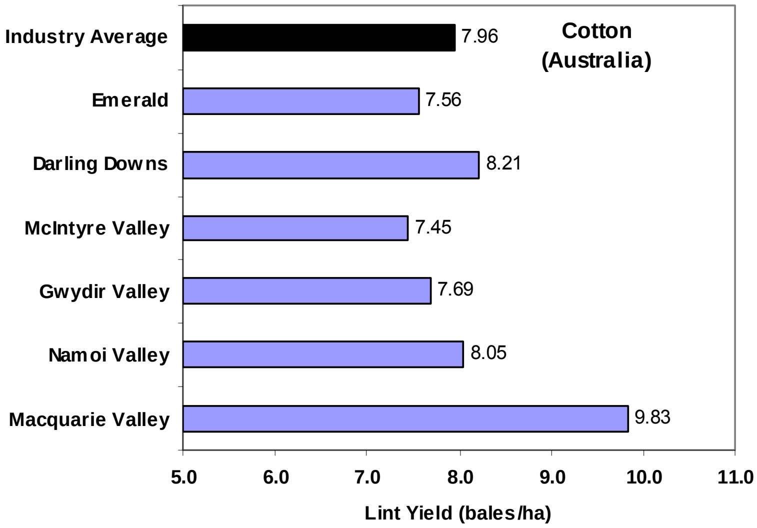


Figure 27. Cotton lint yields for different valleys in Queensland and New South Wales, Australia. Adapted from average values reported in Table 3 of Tennakoon and Milroy (2003). The Australian cotton industry average is highlighted.

Irrigation Performance Index

The discussion above suggests that a good benchmarking index would depend on the intended purpose. Therefore, if the purpose is to be able to make comparisons across locations and seasons, then the index should be based on net irrigation requirement and should consider differences in yield potential among different areas. An index that takes these factors into account could be defined as:

$$IPI = (Y/Yp)/(I/NIR). \qquad (8)$$

$$NIR = ET + SLR - Erain - [ASWs - ASWm] \qquad (9)$$

where, IPI = irrigation performance index, Y = actual crop yield, Yp = potential crop yield, I= irrigation, NIR = net irrigation requirement, ET = evapotranspiration, SLR = salt leaching requirements, ERain= effective in-season rainfall, ASWs = available soil water at sowing, which is the available water stored in the soil profile to the maximum effective root depth, ASWm = available soil water at maturity (or defoliation for cotton). The IPI would be unitless, the yields could be expressed in kg/ha or bales/ha, and the water components in mm or ML/ha.

The IPI penalizes low yields and water waste, but it considers differences in yield potential and NIR among regions and seasons. The Yp and NIR values needed to calculate the IPI could be developed by regions, and even by farm, and field scales. The challenge for the industry is to put in place procedures for collecting the data necessary to calculate the IPI. The IPI, however, is unitless and does not provide information on “bales/ML” that the industry is seeking and that farmers understand, and therefore it would be more appropriate to use it in combination with the more familiar indices.

Cotton Water Use Efficiency Review

Data Sources and Quality

This report includes data at several scales and with varying quality. It includes WUE data at the international, national, valley, farm, and field levels. It also includes a review of research data at the plot-size scale, and also data collected by farmers and crop consultants at the commercial production scale. Data differ in quality since some of them were measured while others were estimated. Differences in the calculated WUE's also arise from the fact that data collected from different applications did not necessary follow the same procedures for measuring or estimating data. To guide the reader, comments about the quality of data will be made as they are presented.

Australian Research Water Use Efficiency Data

Irrigation Frequency Study, Biloela, 1962/63 to 1963/64

Keefer et al. (1990) reported GPWUI, IWUI, and water balance values from irrigation frequency studies with furrow irrigation conducted during the 1962/63 and 1963/64 seasons at Biloela, Australia (Table 11). The GPWUI and IWUI during the study averaged 0.71 and 1.40 bales/ML, respectively, with considerable variations among treatments. Figure 60 shows that during both seasons, the IWUI decreased with irrigation frequency, as more water was applied. The GPWUI varied much less with irrigation frequency compared to the IWUI. Both indices were higher in the second season, mainly due to much higher yields. The maximum yield during the second season reached 7.89 bales/ha, which was very high for the 1960's, which was almost twice the maximum yield obtained in the previous year of the study.

Table 11. Gross production water use index (GPWUI= lint yield/total water) and irrigation water use index (IWUI =lint yield/irrigation) obtained from cotton irrigation frequency experiment during two seasons at Biloela, Australia. Adapted from data reported by Keefer et al. (1990).

Season	Treatment	# of in-crop Irrigations	PAW*	Pre-Irrigation (mm)	In-crop Irrigation (mm)	Total Irrigation (mm)	Effective Rain (mm)	Rain+Total Irrigation (mm)	Lint yield (kg/ha)	Lint yield (bales/ha)	GPWUI |---(kg/ha/mm)---|	IWUI	GPWUI |---(bales/ML)---|	IWUI
1962/63	Rain Grown	0		150	0	150	412	562	743	3.27	1.32	4.95	0.58	2.18
	Very Infrequent	1		150	107	257	412	669	952	4.19	1.42	3.70	0.63	1.63
	Infrequent	3	80%	150	256	406	412	818	972	4.28	1.19	2.39	0.52	1.05
	Frequent	4	60%	150	275	425	412	837	933	4.11	1.11	2.20	0.49	0.97
	Very Frequent	6	40%	150	263	413	412	825	867	3.82	1.05	2.10	0.46	0.92
1963/64	Rain Grown	0		150	0	150	234	384	746	3.29	1.94	4.97	0.86	2.19
	Very Infrequent	2		150	305	455	234	689	1225	5.40	1.78	2.69	0.78	1.19
	Infrequent	4	80%	150	350	500	234	734	1585	6.98	2.16	3.17	0.95	1.40
	Frequent	6	60%	150	465	615	234	849	1692	7.45	1.99	2.75	0.88	1.21
	Very Frequent	8	40%	150	488	638	234	872	1791	7.89	2.05	2.81	0.90	1.24
Average 1962/63		**2.8**		**150**	**180**	**330**	**412**	**742**	**893**	**3.94**	**1.22**	**3.07**	**0.54**	**1.35**
Average 1963/64		**4.0**		**150**	**322**	**472**	**234**	**706**	**1408**	**6.20**	**1.99**	**3.28**	**0.87**	**1.44**
Overall average		**3.4**		**150**	**251**	**401**	**323**	**724**	**1151**	**5.07**	**1.60**	**3.17**	**0.71**	**1.40**

* PAW is the plant available water at which irrigation was applied

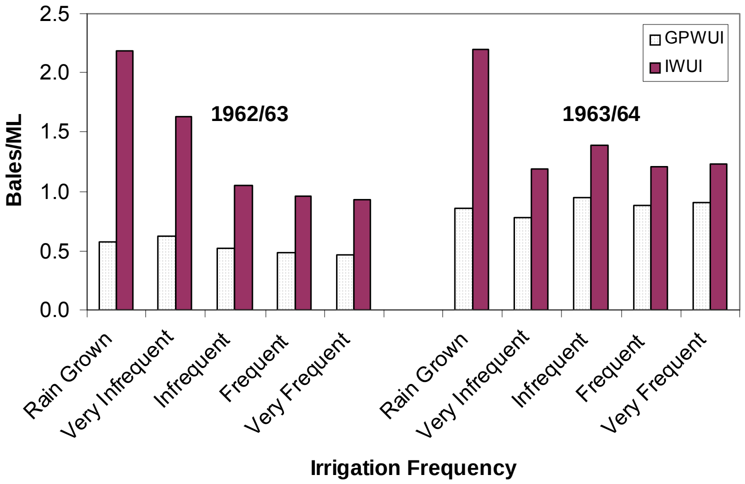


Figure 28. Cotton gross production water use index (GPWUI= lint yield/total water) and irrigation water use index (IWUI =lint yield/irrigation) as a function of irrigation frequency during two seasons at Biloela, Australia. Adapted from data reported by Keefer et al. (1990). All treatments, including the "Rain Grown" treatment received 150 mm of pre-sowing irrigation.

Deficit irrigation experiment, Narrabri, 1975/76 and 1976/77

Cull et al. (1981) reported data from an experiment conducted at Narrabri, Australia, during the 1975/76 and 1976/77 growing seasons (Table 26). This experiment compared the yield response of cotton to different levels of irrigation, including dryland, deficit-irrigated, and fully-irrigated treatments. The yields in this study were very low compared with current yield potentials. The maximum yield in this study was just 4.17 bales/ha, which is less than half of the average yield obtained from the crop competition data (9.38 bales/ha), with much higher yields obtained during individual yields in the order of 12 bales/ha. This is an indication of the yield improvement obtained in the Australian cotton industry over the last 35 years. Because of the low yields, the CWUI and GPWUI obtained in this study were also low and averaged only 0.49 and 0.42 bales/ML of ET and total water, respectively.

Table 12. Cotton water use indices obtained at Narrabri, Australia. Adapted from data reported by Cull et al. (1981) for the 1975/76 and 1976/77 seasons using furrow irrigation.

Season	# irrig	Total Water	ET	Rain	Yield	Yield	CWUI	GPWUI	CWUI	GPWUI
		|-----------------(mm)-------------------|			(bales/ha)	(kg/ha)	|---------kg/ha/mm---------		|-------bales/ML--------|	
1975/76	2	852	662	550	4.02	913	1.38	1.07	0.61	0.47
	1	797	659	550	4.07	924	1.40	1.16	0.62	0.51
	0	704	704	550	4.17	947	1.34	1.34	0.59	0.59
1976/77	3	945	775	502	4.12	935	1.21	0.99	0.53	0.44
	2	891	743	502	3.87	878	1.18	0.99	0.52	0.43
	1	779	689	502	3.50	795	1.15	1.02	0.51	0.45
	1	800	680	502	2.37	538	0.79	0.67	0.35	0.30
	0	634	607	502	1.30	295	0.49	0.47	0.21	0.21
Average	**1.25**	**800**	**690**	**520**	**3.43**	**778**	**1.12**	**0.96**	**0.49**	**0.42**

CWUI =crop water use index (lint yield/ET), GPWUI = gross production water use index (lint yield/total water)
ET = evapotranspiration

Irrigation Frequency Studies, Emerald, 1978/79 to 1983/84

Keefer et al. (1990) reported GPWUI and IWUI values from several irrigation frequency experiments conducted during the 1978/79 and 1979/80 seasons at Emerald (Table 13). The experiments were conducted at different sites, including different soil types. The GPWUI ranged from 0.72-1.16 bales/ML and averaged 0.91 bales/ML. The IWUI ranged from 1.46-2.30 bales/ML and averaged 1.69 bales/ML.

Table 13. Gross production water use index (GPWUI= lint yield/total water) and irrigation water use index (IWUI =lint yield/irrigation) obtained from four cotton irrigation frequency experiments during two seasons at Emerald, Australia. Adapted from data reported by Keefer et al. (1990).

Season	Treatment	# of in-crop Irrigations	GPWUI	IWUI	GPWUI	IWUI
			|---(kg/ha/mm)---|		|---(bales/ML)---|	
1978/79	E1-W1(F)*	5	2.2	3.43	0.97	1.51
1978/79	E1-W2(F)	3	2.25	3.56	0.99	1.57
1979/80	E2-W3(F)	4	1.81	3.32	0.80	1.46
1979/80	E2-W4(VIF)	1	1.64	3.81	0.72	1.68
1979/80	E3-W5(F-IF)	3	2.64	5.22	1.16	2.30
1979/80	E4-W6(VIF-F)	2	1.87	3.63	0.82	1.60
Average		**3.0**	**2.07**	**3.83**	**0.91**	**1.69**
Maximum			**2.64**	**5.22**	**1.16**	**2.30**
Minimum			**1.64**	**3.32**	**0.72**	**1.46**

* E is the experiment #, W is the treatment #,
F, IF, and VIF denote frequent, infrequent and very infrequent irrigation
Treatments also received pre-irrigation

GPWUI and IWUI values for furrow-irrigated cotton measured at Emerald during the 1982/83 and 1983/84 seasons were also reported by Keefer (1989) and Keefer (No date) (Table 14). Both the GPWUI and IWUI varied with season and irrigation treatment, with the GPWUI being much more consistent than the IWUI. The GPWUI and IWUI averaged 1.45 and 2.67 bales/ML of total water and irrigation, respectively. As expected, the IWUI tended to decrease as the number of irrigation increased, which suggest that in this area a positive dryland yield could be obtained during the two seasons (Fig. 29).

Table 14. Cotton Gross production water use index (GPWUI=lint yield/total water) and irrigation water use index (IWUI = lint yield/irrigation) obtained at Emerald during two seasons (Keefer, 1989).

Season	Deficit (mm)	Number Irrigations	Yield (kg/ha)	Yield (bales/ha)	GPWUI	IWUI	GPWUI	IWUI
					|------(kg/ha/mm)------|		|------(bales/ML)------|	
1982/83	45	11	1890	8.33	2.6	3.5	1.15	1.54
	75	7	2025	8.92	2.9	4.2	1.28	1.85
	120							
	150	3	1575	6.94	2.5	4.6	1.10	2.03
1983/84	45	7	1877	8.27	3.6	5.6	1.59	2.47
	75	5	2054	9.05	3.8	5.9	1.67	2.60
	120	2	2002	8.82	3.9	10.8	1.72	4.76
	150	3	1967	8.67	3.8	7.8	1.67	3.44
Average			**1913**	**8.43**	**3.3**	**6.06**	**1.45**	**2.67**

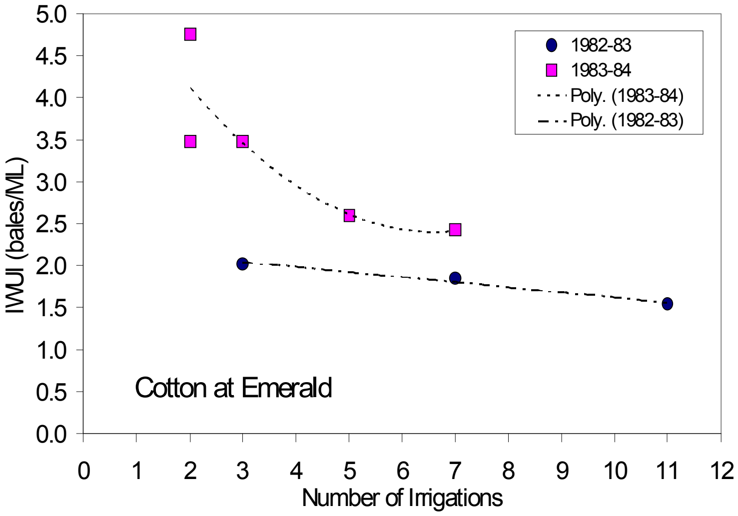


Figure 29. Cotton irrigation water use index (IWUI = lint yield/irrigation) as a function of number of irrigations obtained during two seasons at Emerald. Adapted from data reported by Keefer (No date).

WUE from drip and furrow irrigation at Narrabri in the 1980's

Hodgson et al. (1990) compared the performance of surface drip, buried drip, and furrow irrigation over four seasons (1983/84 –1986/87) at Narrabri, Australia. Summary results (Table 15) show that less irrigation was applied with the furrow system than with the drip systems, which is contrary to what is normally expected. On average over the four seasons, the drip systems received 4.4 ML/ha, while the furrow received 3.6 ML/ha. Similar lint yields for all three systems, averaging 7.58 bales/ha, suggests that the drip treatments were probably over-irrigated. Because of this, no advantage in CWUI or IWUI was obtained in this study from using drip compared to furrow. Quite the opposite, in this study higher IWUI was obtained with the furrow system. This is contrary to the results normally expected (Raine and Foley, 2002). For instance, in a similar experiment comparing drip to surface irrigation in Uzbekistan, Kamilov et al. (2002) found that drip irrigation combined with optimal irrigation scheduling improved cotton seed yields by 21-22% with 31-39% less irrigation water, compared to surface irrigation. These results show that IWUI values not only depend on the type of irrigation system, but also depend on how the irrigation system is managed. Therefore, it is not enough for the industry to change from furrow to lateral move or centre pivot systems if this change is not accompanied by improved irrigation water management and irrigation scheduling.

The CWUI in this study averaged 0.99 bales/ML of ET for all treatment-years, which are lower than those reported by Tennakoon and Milroy (2003) and Goyne et al. (2000), which is mainly the result of the lower cotton yields obtained in this study. The lower yields in this study could be an indication of improvements in varieties and crop management that have taken place in the Australian cotton industry since the late 1980's. The IWUI values in this study were, however, higher than those reported by Tennakoon and Milroy (2003) and Raine and Foley (2002), which have to be the result of less irrigation water applied, since yields were lower.

Table 15. Cotton water use indices for three irrigation systems obtained during four seasons (1983/84-1986/87) at Narrabri, Australia. Adapted from values reported in Table 1 of Hodgson et al. (1990).

		Irrigation	Eff. Rain	Soil water	ET	Yield	Yield	CWUI	IWUI	CWUI	IWUI
System	Season	|------------------------- mm			-----------------------	(kg/ha)	(bales/ha)	|--- kg/ha/mm	---|	|-- bales/ML	---|
Surface Drip	1983/84	122	484	90	696	1684	7.42	2.42	13.82	1.07	6.09
Surface Drip	1984/85	497	193	3	693	1933	8.52	2.79	3.9	1.23	1.72
Surface Drip	1985/86	616	244	39	899	1924	8.48	2.14	3.12	0.94	1.37
Surface Drip	1986/87	507	284	67	858	1287	5.67	1.5	2.54	0.66	1.12
Buried Drip	1983/84	149	502	82	733	1671	7.36	2.28	11.2	1.00	4.93
Buried Drip	1984/85	524	187	-41	670	1883	8.29	2.81	3.6	1.24	1.59
Buried Drip	1985/86	585	229	30	844	2093	9.22	2.48	3.58	1.09	1.58
Buried Drip	1986/87	497	282	71	850	1326	5.84	1.56	2.67	0.69	1.18
Furrow	1983/84	89	506	112	707	1619	7.13	2.29	18.2	1.01	8.02
Furrow	1984/85	485	215	86	786	1879	8.28	2.39	3.65	1.05	1.61
Furrow	1985/86	443	255	56	754	1870	8.24	2.48	4.22	1.09	1.86
Furrow	1986/87	418	281	72	771	1473	6.49	1.91	3.52	0.84	1.55
Averages:											
Surface Drip	4 seasons	436	301	50	787	1707	7.52	2.21	5.85	0.97	2.57
Buried Drip	4 seasons	439	300	36	774	1743	7.68	2.28	5.26	1.01	2.32
Furrow	4 seasons	359	314	82	755	1710	7.53	2.27	7.40	1.00	3.26
All Systems	***4 seasons***	***411***	***305***	***56***	***772***	***1720***	***7.58***	***2.25***	***6.17***	***0.99***	***2.72***

CWUI = crop water use index (lint yield/ET), IWUI = irrigation water use index (lint yield/irrigation), ET = evapotranspiration

WUE from cropping systems and tillage research at Narrabri

A long-term cropping system and tillage research was conducted at Narrabri, Australia, from 1993/94 to 2002/03. The experiment compared cotton crop water use index (CWUI= lint yield/ET) from three crop rotation and tillage combinations, including Conventional Tillage-Continuous Cotton (CT-CC), Minimum Tillage- Continuous Cotton (MT-CC), and Minimum Tillage- Cotton-Wheat rotation (MT-CW). Results from this experiment have been reported by Tennakoon (2000), Tennakoon and Hulugalle (2006), and Tennakoon et al. (1998). Results are summarized in Figure 30, which show considerable seasonal variation in CWUI for all cropping systems. The overall average for all treatment-years was 0.87 bales/ML of ET, with differences among cropping systems. Increases in CWUI were obtained by minimum tillage compared to conventional tillage and by growing wheat in rotation with cotton as opposed to continuous cotton. Both of these strategies are known to conserve soil water and therefore would have a positive effect on CWUI. The average CWUI values reported in this study are, however, lower than those reported by Goyne et al. (2000), Tennakoon and Milroy (2003), and Tennakoon et al. (2004).

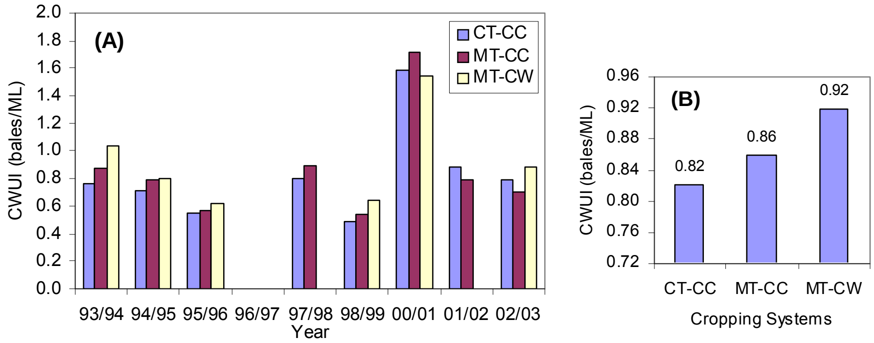


Figure 30. Cotton crop water use index (CWUI=lint yield/evapotranspiration) from crop rotation and tillage experiment at Narrabri, Australia. Adapted from data reported by Tennakoon (2000), Tennakoon and Hulugalle (2006), and Tennakoon et al. (1998). CT = conventional tillage, MT = minimum tillage, CC = continuous cotton, CW = cotton-wheat rotation. (A) Yearly averages, (B) Averages including all years.

WUE from different row configurations

In Australia, cotton producers use different row configurations, including solid, single skip, double skip, wide row, and alternate skip (Bange and Stiller, 2002) (Figures 31 and 32).

Figure 31. Cotton planted on alternate skip row configuration near Emerald, Australia (Photo by Jose Payero).

Figure 32. Cotton planted on single skip row configuration in the Darling Downs, Australia (Photo by Jose Payero).

Although skip-row configurations instead of solid configurations are mainly used in dryland production, they are also being used in irrigated cotton in situations where water is limited. Results of research comparing yields of solid to single skip and double skip cotton in Australia have been reviewed by Bange and Stiller (2002), and Gibb (1995). Gibb (1995) suggested the following equations:

$$Yss = 0.82Ys + 0.36 \qquad (1)$$

$$Yds = 0.58\ Ys + 0.79 \qquad (2)$$

Where, Yss = single skip yield, Yds = double skip yield, Ys = solid yield, all in units of bales/ha. The equations were derived from over 30 separated irrigated and dryland experiments conducted during 1984-1993 in Central Queensland and the Darling Downs. Relationships from other studies were also reported by Bange and Stiller (2002) and Goyne and Hare (1999) (Fig. 33). Plotting equations 17 and 18 (Fig. 34) shows that Ys>Yss>Yds, except for very low yield levels (ie. Yields < 2.5 bales/ha).

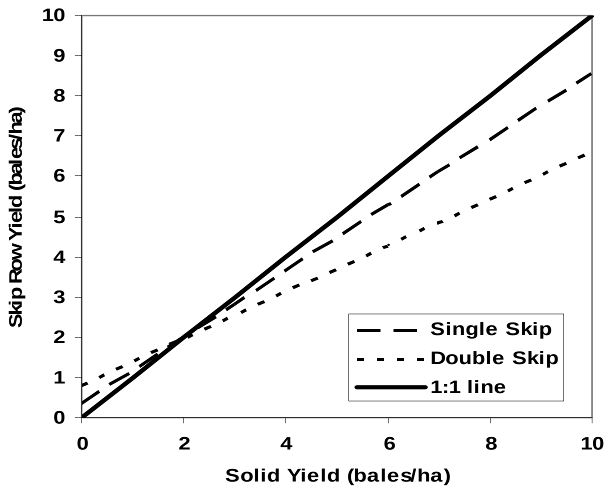


Figure 33. Relationships between cotton yields of solid row and skip row configuration reported by Gibb (1995).

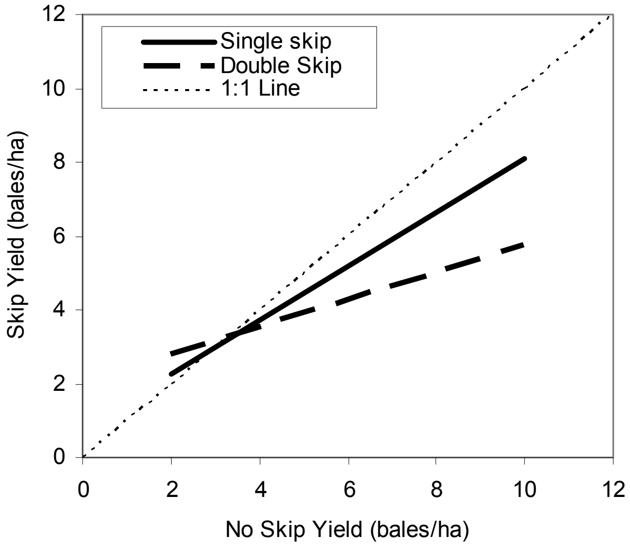


Figure 34. Relationships between cotton yields of solid row and skip row configuration reported by Goyne and Hare (1999).

Therefore, based on these results, the configurations with higher yields will also tend to have higher WUE in terms of bales/ML, as illustrated in Table 16 and Figure 35.

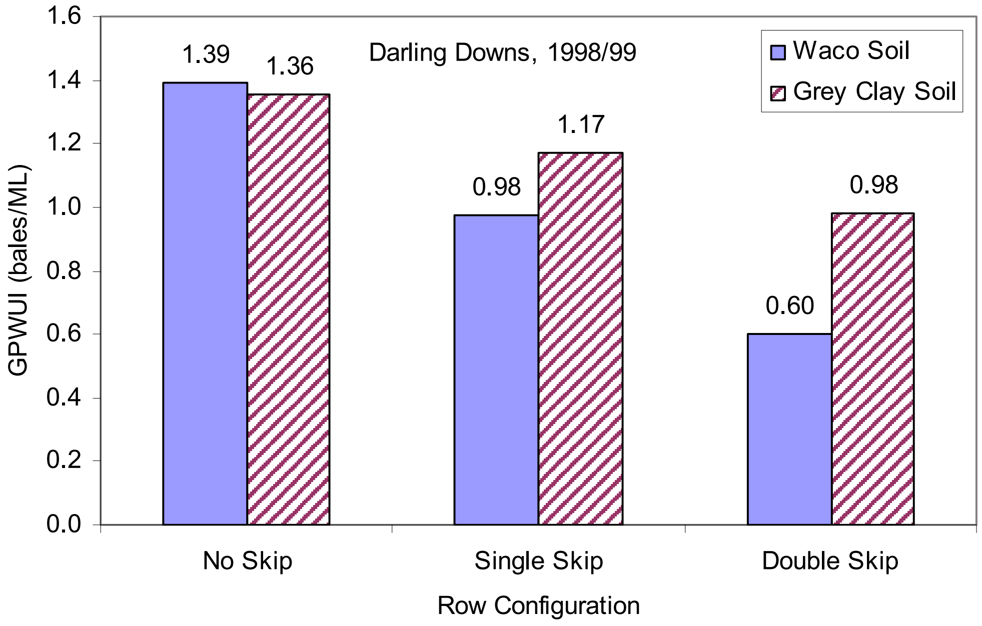


Figure 35 Gross production water use index (yield/[soil water + rain]) for dryland cotton obtained with different row configurations and two soil types (Goyne and Hare, 1999).

Table 16 Water balance and cotton water use efficiency indices obtained from several fields and row configurations during the 1994/95 season. Adapted from data in Table 2 (page 97) of Gibb (1995).

Row Configuration	Field #.	Irrigation	Rainfall	Total	Yield	GPWUI	IWUI
		(ML/ha)			(bales/ha)	(bales/ML)	
Solid	105	2.87	0.80	3.67	8.60	2.34	3.00
	106	3.68	1.04	4.72	8.79	1.86	2.39
	135	4.88	0.69	5.57	8.52	1.53	1.75
	136	4.99	0.79	5.78	9.24	1.60	1.85
	137	4.77	1.03	5.80	8.67	1.49	1.82
Double Skip	131	3.24	1.84	5.08	4.59	0.90	1.42
	133	3.69	1.72	5.41	4.20	0.78	1.14
	134	3.79	2.00	5.79	4.92	0.85	1.30
Single Skip	319	2.00	0.98	2.98	2.72	0.91	1.36
	110	2.00	2.30	4.30	3.70	0.86	1.85
Averages:							
Solid		4.24	0.87	5.11	8.76	1.77	2.16
Double Skip		3.57	1.85	5.43	4.57	0.84	1.28
Single Skip		2.00	1.64	3.64	3.21	0.89	1.61

GPWUI =gross production water use index (yield/total water)
IWUI = irrigation water use index (yield/irrigation)

Although skip row configurations give up yield potential compared with solid planting when water is not severely limited, they reduce risk of crop failure when water is limited. Also, since production costs can be significantly reduced with skip row, especially for Bollgard II varieties with high seed cost, Gibb (1995) suggested that gross margins per unit area ($/ha) could actually increase with skip row compared to solid planting. Goyne and Hare (1999) reported gross margins for single and double skip raingrown crops of $532/ha and $604/ha, respectively, compared with only $398/ha for solid planting. Additional potential income from skip row configurations under water limiting situations can also derive from the premium price due to improved fibre quality compared to solid planting. Goyne and Here (1999) reported improved quality from skip row configurations in raingrown cotton compared to solid planting (Figure 36).

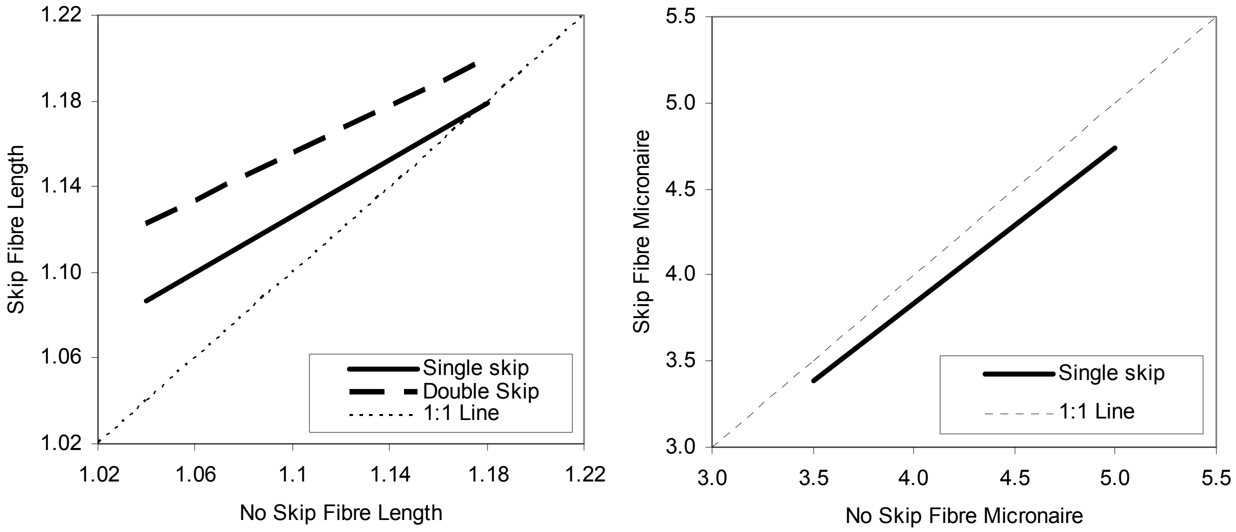


Figure 36. Effect of row configurations on cotton fibre quality parameters (fibre length and micronaire) reported by Goyne and Hare (1999)

WUE from drip and furrow systems at Emerald

McHugh (2003) reported results of comparison of WUE from subsurface drip (SDI) and furrow system over two seasons (2001/02 and 2002/03) at a location 23 km east of Emerald, Australia. Four irrigation treatments were applied with the SDI system, with irrigation representing 50, 75, 90, and 105 % (120% in the first season) of the estimated crop evapotranspiration. Average results for the two seasons, including water balance data, yield, and GPWUI are shown in Table 17. Only GPWUI is shown since irrigation data were not given, therefore IWUI could not be calculated. Although ETc data was given the CWUI was not calculated since close examination of the data revealed that a plot of yield versus ET would result in an intercept of about 5.5, suggesting that a cotton lint yield of 5.5 bales/ha could be produced with ET=0. Since this is impossible, it was presumed that the ET values were underestimated and the CWUI was not calculated.

Two sets of GPWUI values are shown in Table 17, one recalculated from the yield and water balance data (based on rainfall, applied water less tail water) as specified in the original source, and the other set is the values originally reported in Table 2 of McHugh (2003). For some unknown reason, the two sets of GPWUI values do not coincide. The recalculated values were higher for SDI and lower for the furrow system compared to the values given in the original source. Table 17 shows higher yields for the furrow system compared to SDI, which were due to fertiliser shortages in the SDI treatments (as indicated in the original source). As expected, the GPWUI for SDI tended to decrease as more water was applied. On average, the recalculated GPWUI was higher for SDI (1.42 bales/ML) compared to furrow (1.29 bales/ML). However, the GPWUI as originally reported shows the opposite.

Table 17. Average results from comparison of subsurface drip (SDI) and furrow systems at Emerald, Australia, during the 2001/02 and 2002/03 seasons. The SDI treatments were irrigated at 50, 75, 90 and 105% of crop evapotranspiration. Adapted from data in figure 4 and Table 2 of McHugh (2003).

	SDI 50%	SDI 75%	SDI 90%	SDI 105%	Avg. SDI	Furrow
Runoff (mm)	0	0	0	32	8	224
Drainage (mm)	14	-12	17	65	21	114
ETc (mm)	413	529	601	616	540	649
Irrigation + Rain (mm)	427	518	617	713	569	986
Lint yield (bales/ha)	7.24	8.23	8.26	8.09	7.95	9.82
GPWUI (bales/ML)-recalculated	1.70	1.59	1.34	1.19	1.42	1.29
GPWUI (bales/ML)-as reported in McHugh (2003)	1.65	1.52	1.32	1.13	1.40	1.48

GPWUI=gross production water use index [Lint yield/(irrigation + rain - runoff)]

Although SDI can have irrigation efficiency of almost 100%, some disappointing results have been obtained in cotton in Australia (Hodgson et al., 1990). It has been suggested that in the heavy clay soils in which cotton is grown in Australia, the high irrigation frequencies needed with SDI result in temporal waterlogging, and associated hypoxic/anoxic rhizosphere conditions, that affect crop development and yield. To address this problem, an experiment at Emerald is currently investigating the benefits of oxygenation through the SDI system. To oxygenate the water in this experiment, air is sucked in as water is applied with the SDI system, using a venturi device (Figure 37).

Figure37. Venturi device used by Pendergast and Midmore (2006) to inject air through a subsurface drip irrigation system in a field near Emerald, Australia (photo by Jose Payero).

Among other things, the experiment is comparing WUE from aerated and no aerated treatments, and from irrigation applied to meet either 85 or 105% of estimated crop ET. Preliminary results from the first year (2004/05 season) of the experiment have been reported by Pendergast and Midmore (2006), which are summarized in Table 18. They obtained significantly higher yields, CWUI, and better root development when aeration was applied, compared with no aeration. Similar increases in yield and CWUI were obtained when the crop was irrigated at 85% ET, compared to 105% ET. These preliminary results suggest potential benefits of aeration with SDI. The higher yields and CWUI obtained with irrigation at 85% ET, however, suggests the need for improving irrigation scheduling with SDI. Overall, the CWUI in this study averaged 1.08 bales/ML, which is almost the same as the average 1.09 bales/ML reported by Tennakoon and Milroy (2003) for Emerald.

Table 18. Preliminary results of experiment evaluating oxygenation through subsurface drip irrigation for cotton during the 2004/05 season at Emerald, Australia. Adapted from preliminary results reported by Pendergast and Midmore (2006).

Variable	Treatment	Lint Yield (bales/ha)	Yield Increase	CWUI* (bales/ML)	CWUI Increase	Tap & Fibrous roots (g)
Aeration	No aeration	7.35		0.953		25.73
	Aeration	9.31	21%	1.208	21%	30.11
Irrigation	85% ET	9.22	19%	1.266	29%	26.40
	105% ET	7.45		0.895		29.44
Average		**8.33**		**1.081**		**27.92**

* CWUI = crop water use index (lint yield/crop evapotranspiration)

WUE from alternative management of sprinkler irrigation

An experiment comparing alternative management of large mobile irrigation machines to irrigate cotton in the Darling Downs was conducted by White and Raine (2004) in the 2002/03 season. They compared several Regulated Deficit Irrigation (RDI) and Partial Rootzone Drying (PRD) treatments. They were not able to reach a conclusion about the potential of PRD to improve WUE due to the low irrigation frequencies applied and to the amount and timing of in-crop rain. However, they were able to obtain valuable data from the RDI treatments. They found that cotton yields were maximized by applying 50% of the irrigation water that was normally applied commercially using a lateral move irrigation machine, which corresponded to replacing around 79% of potential evapotranspiration (ETo). No yield response was obtained by applying more than 50% of the irrigation applied in commercial applications. These results suggest potential improvement in the way commercial operations manage these machines. These results point out that these machines can save water if they are managed correctly, but they can waste as much water as a surface system if managed incorrectly. The IWUI values from this study varied with irrigation treatment between 0.88 and 1.17 bales/ML and averaged 1.0 bales/ML (Table 19). Figure 38 shows that the IWUI increased significantly when irrigation increased from 25 to 50% of commercial practice, but linearly declined as additional water was applied. Based on the decreasing tendency of IWUI with irrigation amount previously shown from other datasets, it is odd that in this study the IWUI increased when irrigation increased from 25 to 50% of irrigation applied compared to commercial practice.

Table 19. Irrigation water use index (IWUI = lint yield/irrigation) for cotton irrigated by a lateral move irrigation machine in the Darling Downs (Adapted from White and Raine, 2004).

%Eto Replaced by Irrigation	Irrigation (% of commercial)	IWUI (bales/ML)
71	25	0.99
79	50	1.17
86	75	1.00
93	100	0.94
100	125	0.88
Average		1.00

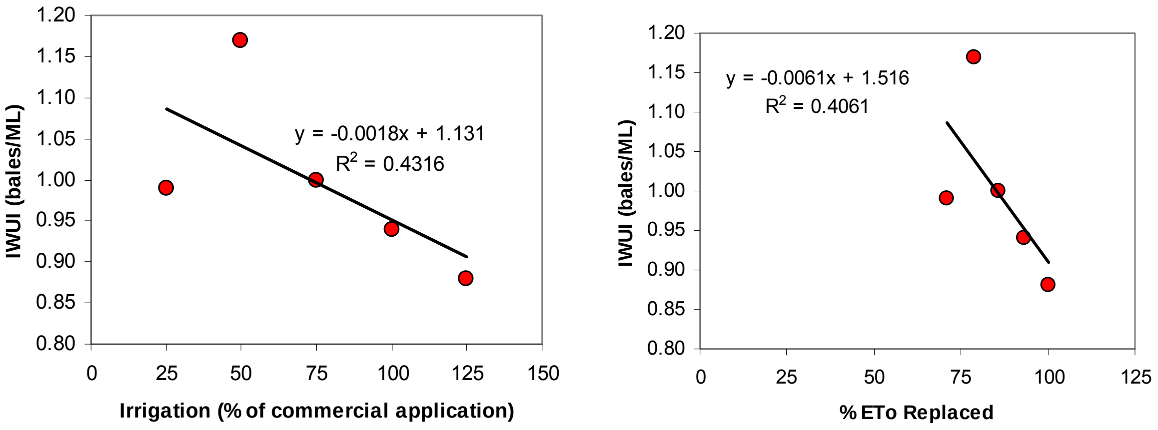


Figure 38. Irrigation water use index (IWUI = lint yield/irrigation) for cotton irrigated by a lateral move irrigation machine in the Darling Downs as a function of irrigation applied and % of potential evapotranspiration (ETo) replaced by irrigation. Adapted from White and Raine (2004).

WUE from Bollgard® II and conventional varieties

Richards et al. (2006) compared GPWUI and IWUI from Bollgard® II and conventional versions of the same genotype under 5 patterns of moisture stress. Preliminary data from the first two seasons (2004/05 and 2005/06) of this study (Table 20) show that the average yields and GPWUI for the Bollgard® II and conventional varieties were practically the same for each of the two seasons. The average IWUI was about the same for the two varieties during the second season. During the first season, however, the IWUI was higher for the Bollgard® II variety, which was due to the conventional variety receiving an average of 0.8 ML/ha more irrigation, which did not result in significant yield increase. Figure 39 shows that during both seasons, yields from the two varieties responded almost linearly to irrigation. Two points (one for each variety), however, did not fit the line, which produced high yields with little irrigation, which point out the importance of proper irrigation timing. These outliers corresponded to the “skip 4th and 5th irrigations” treatment, which suggests that the 4th and 5th irrigations were either not needed, or that timely rainfall was able to meet crop water requirements late in the season. These results also suggest that treatments receiving the 4th and 5th irrigations were actually over-irrigated during that season. However, because of the stochastic nature of rainfall, perfect irrigation scheduling is not always possible, even under the best management, although the use of available scheduling techniques and tools could help improve irrigation scheduling. Future developments in weather forecasting and their integration into decision support tools should provide additional scheduling skills. Figure 40 shows that similarly to other datasets, both the GPWUI and IWUI in this study decreased with total water and irrigation, respectively.

Table 20. Cotton gross production water use index (GPWUI = lint yield/total water) and irrigation water use index (IWUI = lint yield/irrigation) obtained at Narrabri, Australia, during the 2004/05 and 2005/06 seasons. Adapted from preliminary results reported by Richards et al. (2006).

Treatment	**Total Water**	**Irrigation**	**Yield**	**GPWUI**	**IWUI**
	(ML/ha)	**(ML/ha)**	**(bales/ha)**	**|-----(bales/ML)------|**	
2004/05 season:					
Bollgard full irrigatrion	14.0	6.9	9.5	0.68	1.38
Conventioanal full irrigation	14.8	7.8	9.1	0.61	1.17
Bollgard skip 1st	13.0	5.8	7.4	0.57	1.28
Conventional skip 1st	13.8	6.6	7.5	0.54	1.14
Bollgard skip 2nd	13.2	6.0	9.3	0.70	1.55
Conventional skip 2nd	13.6	6.3	9.1	0.67	1.44
Bollgard skip 3rd	12.4	5.2	6.5	0.52	1.25
Conventioanal skip 3rd	13.5	6.4	7.8	0.58	1.22
2005/06 season:					
Bollgard full irrigatrion	11.5	5.7	9.6	0.83	1.68
Conventioanal full irrigation	12.0	6.1	8.5	0.71	1.39
Bollgard skip 1st	10.2	4.5	7.3	0.72	1.62
Conventional skip 1st	10.5	4.5	6.4	0.61	1.42
Bollgard skip 2nd	10.7	5.0	7.3	0.68	1.46
Conventional skip 2nd	10.4	5.0	8.3	0.80	1.66
Bollgard skip 3rd	10.2	4.7	5.7	0.56	1.21
Conventioanal skip 3rd	10.6	4.9	6.9	0.65	1.41
Bollgard skip 4th and 5th	9.4	3.2	9.2	0.98	2.88
Conventional skip 4th and 5th	9.0	3.0	8.5	0.94	2.83
Average 2004/05					
Bollgard	13.2	6.0	8.2	0.62	1.36
Converntional	13.9	6.8	8.4	0.60	1.24
Average 2005/06					
Bollgard	10.4	4.6	7.8	0.75	1.78
Converntional	10.5	4.7	7.7	0.74	1.74

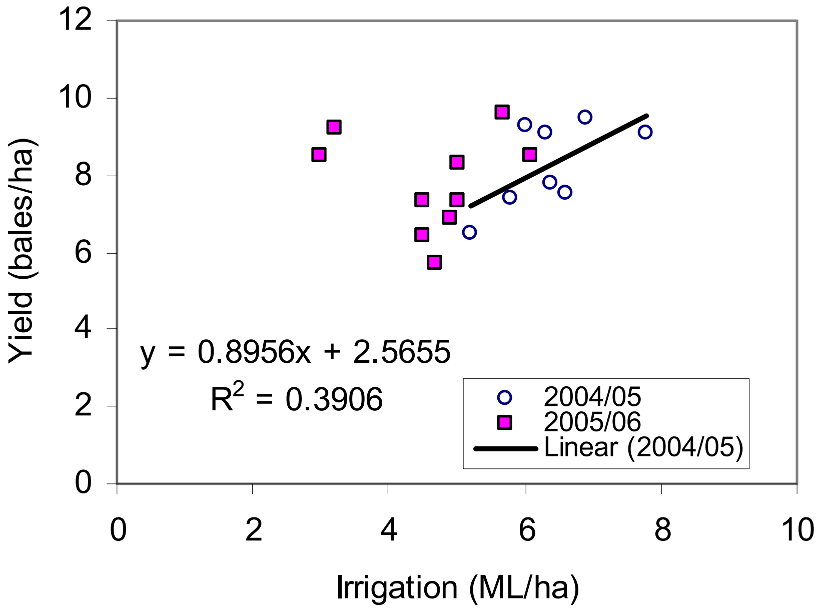


Figure 39. Cotton lint yield response to irrigation obtained at Narrabri, Australia, during the 2004/05 and 2005/06 seasons. Adapted from data reported by Richards et al. (2006).

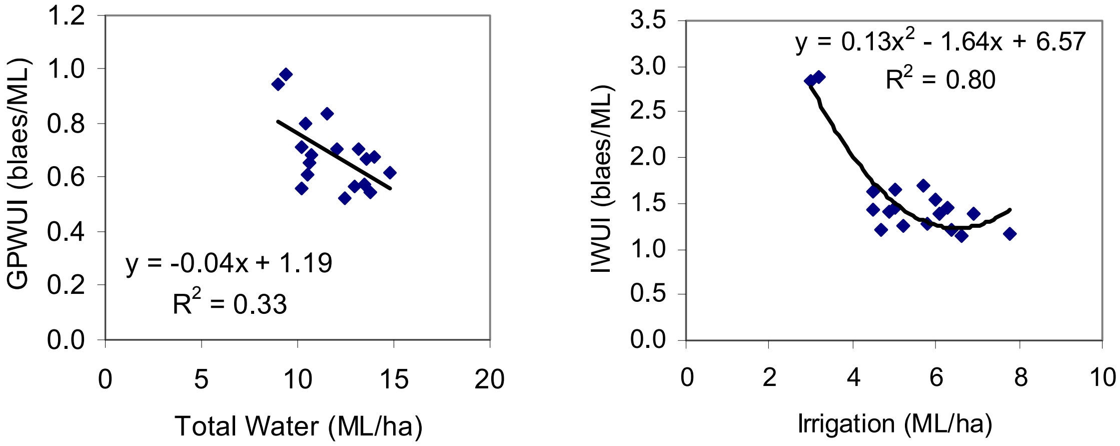


Figure 40. Cotton gross production water use index (GPWUI = lint yield/total water) as a function of total water, and irrigation water use index (IWUI = lint yield/irrigation) as a function of irrigation obtained at Narrabri, Australia, during the 2004/05 and 2005/06 seasons. Adapted from data reported by Richards et al. (2006).

Australian Farm Water Use Efficiency Data

WUE from study by Tennakoon and Milroy (2003)

Tennakoon and Milroy (2003) reported results of a study to estimate water use efficiency and irrigation efficiencies in the Australian cotton industry. They obtained production and water use data from 25 cotton farms and over 200 individual fields representing the six largest cotton production areas in Australia. They estimated ET by calculating a daily water balance for each field using a computer model.

Average results for each production area reported in Tables 1 and 3 of Tennakoon and Milroy (2003) have been summarised in Table 21, which include calculations of net irrigation requirements (NIR), Crop Water Use Index (CWUI =lint yield/ET), Gross Production Water Use Index (GPWUI =lint yield/Total water use), and Irrigation Water Use Index (IWUI =lint yield/irrigation). It was not clear what irrigation values Tennakoon and Milroy (2003) used to calculated IWUI, therefore Table 10 shows calculations using (water pumped + water harvested) (IWUI-a), and only using the water pumped (IWUI-b). The later are closer to the IWUI values reported by Tennakoon and Milroy (2003), but they do not always coincide. The average NIR was either 367 or 461 mm (3.67 or 4.61 ML/ha) depending on whether total rain or used rain within crop was considered in calculating NIR (Table 10). The “total rain” and the “used rain” within crop reported in this study were linearly related as indicated in Figure 41. The slope of the line was 0.59, which suggests that approximately 59% of the rain was effective.

Table 21. Summary results for cotton in six production areas in Australia. Adapted from Tables 1 and 3 of Tennakoon and Milroy (2003).

Region	Lint yield	Total rain **	Used rain	Used Soil Water	Water # Pumped	Water * harvested	Pumped + harvested	Total water use	ET	NIR-a	NIR-b	CWUI	GPWUI	IWUI-a	IWUI-b
	(bales/ha)	mm										bales/ML			
Macquarie Valley	9.83	230	193	83	802	69	871	1097	797	567	604	1.23	0.90	1.13	1.23
Namoi Valley	8.05	455	317	125	502	73	575	1015	771	316	454	1.04	0.79	1.40	1.60
Gwydir Valley	7.69	300	212	121	1231	158	1389	1722	740	440	528	1.04	0.45	0.55	0.62
McIntyre Valley	7.45	442	344	72	394	155	549	965	745	303	401	1.00	0.77	1.36	1.89
Darling Downs	8.21	340	285	139	268	289	557	935	667	327	382	1.23	0.88	1.47	3.06
Emerald	7.56	443	295	108	460	90	550	953	691	248	396	1.09	0.79	1.37	1.64
Industry Average	***8.13***	***368***	***274***	***108***	***610***	***139***	***749***	***1115***	***735***	***367***	***461***	***1.11***	***0.76***	***1.21***	***1.68***

** Total and used rain refers to rain occurring within the growing season

Water pumped from river and bores and used for irrigation

* Water harvested on-farm and used for irrigation

CWUI = crop water use index (lint yield/ET), GPWUI = Gross production water use index (Lint yield/Total Water Use)

NIR-a = net irrigation requirement (ET- Total rain), NIR-b =net irrigation requirement (ET - Used rain)

IWUI-a = Irrigation water use index (Lint yield/(water pumped + water harvested).

IWUI-b = Irrigation water use index (Lint yield/(water pumped).

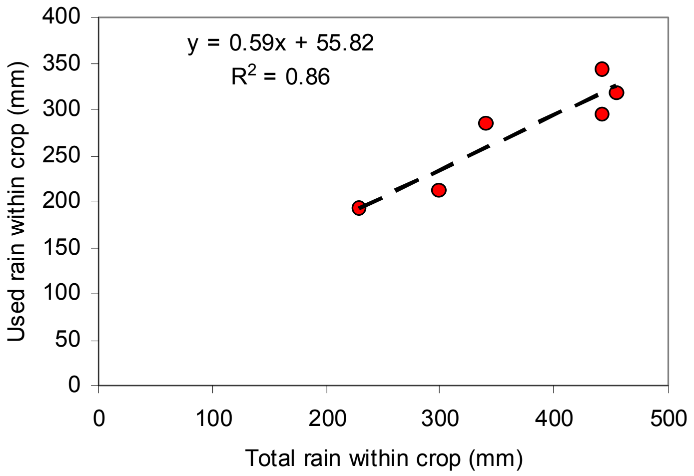


Figure 41. Relationship between total rain within crop and used rain within crop for cotton in six production areas in Australia. Adapted from average values reported by Tennakoon and Milroy (2003).

This study estimated the average on-farm total water input to be over 12 ML/ha. Irrigation applied averaged 829 mm (8.29 ML/ha) (including water pumped + harvested), which was much higher than the NIR, indicating low irrigation efficiencies and opportunity for improving irrigation water management. Tennakoon and Milroy (2003) reported the average irrigation applied as 7 ML/ha, which would just include the water pumped from rivers and bores and did not include the water harvested on-farm and used for irrigation (Table 21). Worth noticing is the data for the Gwydir Valley, which received a lot more irrigation (13.89 ML/ha) than its NIR (4.4 or 5.28 ML/ha). According to this study, a lot more excess irrigation was applied in this area compared to the other valleys.

They found high variability in CWUI values and obtained an average of 1.11 bales/ML of ET (2.5 kg/ha/mm), which is exactly the same as the average values reported by Goyne et al (2000) for the Darling Downs, the McIntyre Valley and Emerald. CWUI values ranged from 1.0 bales/ML in the McIntyre Valley to 1.23 bales/ML, in the Macquarie Valley and the Darling Downs. The GPWUI averaged 0.76 bales/ML of total water, and was particularly low in the Gwydir Valley (0.45 bales/ML). This GPWUI average is much lower than the average obtained from the irrigated crop competition data in the Darling Downs (1.25 bales/ML) (Figure 42). The IWUE (Applied) averaged 1.21 and 1.68 bales/ML of irrigation depending on whether or not water harvested on-farm was used for irrigation (IWUI-a and IWUI-b in Table 10). IWUE (Applied) values were particularly low in the Gwydir Valley (0.55 and 0.62 bales/ML of irrigation). If the IWUI values for the Gwydir Valley are not included, the averages IWUE (Applied) then would increase to 1.35 and 1.89 bales/ML, for the IWUE-a and IWUE-b, respectively. The IWUE-b value for the Darling Downs was particularly high (3.06 bale/ML), which is consistent with the high average value (2.75 bales/ML of irrigation) obtained from the crop competition data reported above. The values of CWUI, GPWUI, and IWUI (Applied) as originally reported by Tennakoon and Milroy (2003) are plotted in Figures 42 to 44 for comparison. Figures 45 and 46 show lint yield and CWUI as a function of ET. Yields were considerable higher in the area with the highest ET (the Macquarie Valley) with no much difference among the other areas, which averaged 7.79 bales/ha. These results, however, do not prove that the high yield obtained at the Macquarie Valley was due to higher ET, since it could have been due to other factors. The CWUI reached a minimum for the areas in which seasonal ET was around 750 mm, increasing for those with higher and lower ET values. This “V-shaped” pattern is driven by the unusually high yields obtained in the Macquarie Valley, compared to the other areas, and by the low ET demands in the Darling Downs.

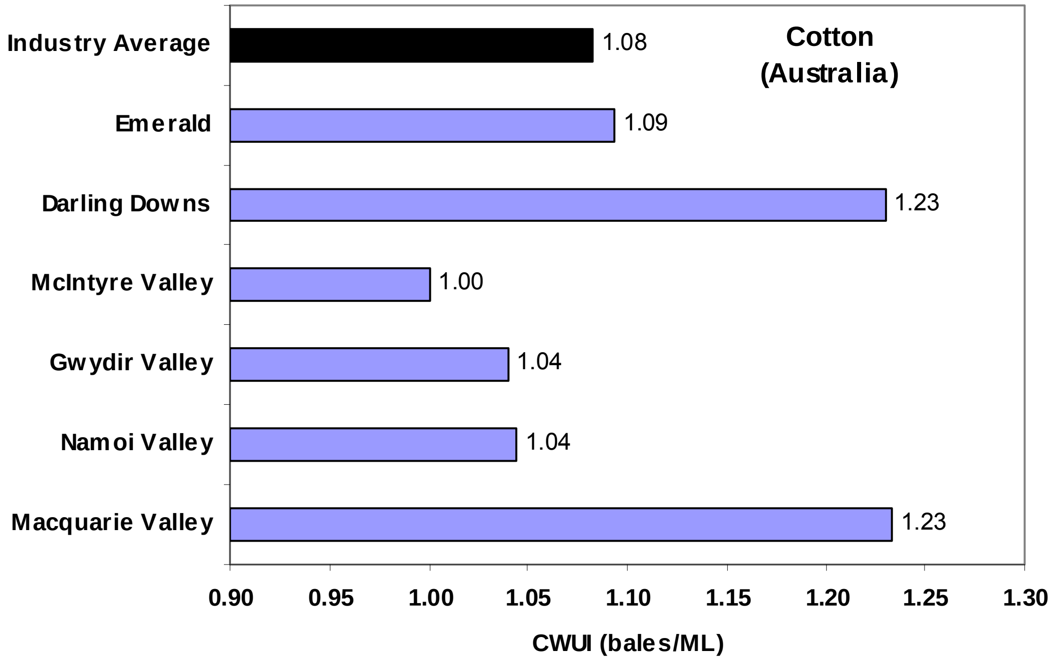


Figure 42. Crop water use index (CWUI=Lint yield /evapotranspiration) obtained in the different cotton producing valleys in Queensland and New South Wales, Australia. Adapted from average values reported in Table 3 of Tennakoon and Milroy (2003). The Australian cotton industry average is highlighted.

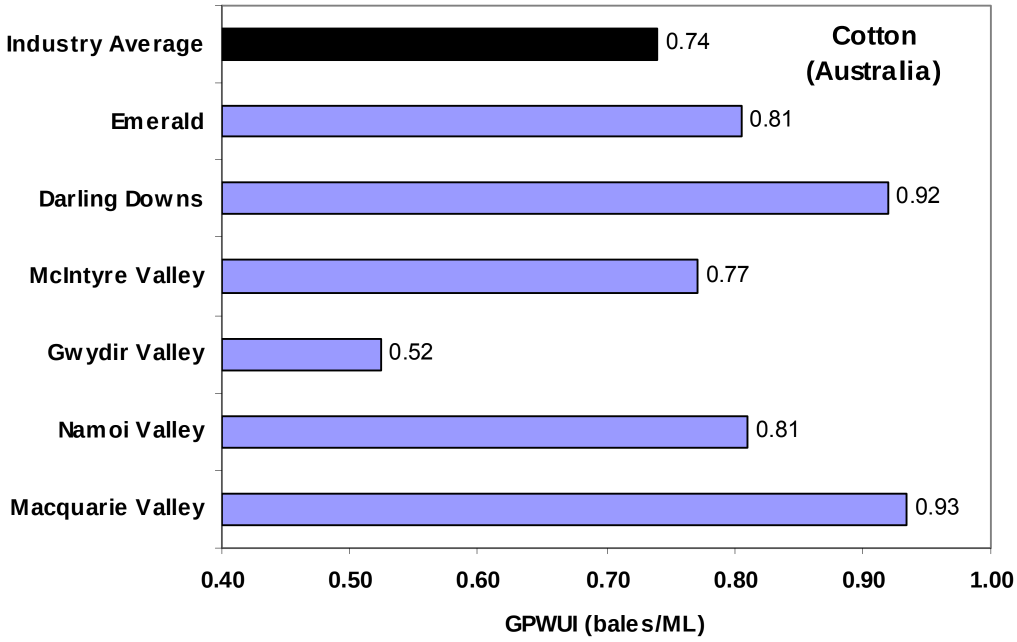


Figure 43. Gross Production Water Use Index (GPWUI=Lint yield /Total water inputs) obtained in the different cotton producing valleys in Queensland and New South Wales, Australia. Adapted from average values reported in Table 4 of Tennakoon and Milroy (2003). The Australian cotton industry average is highlighted.

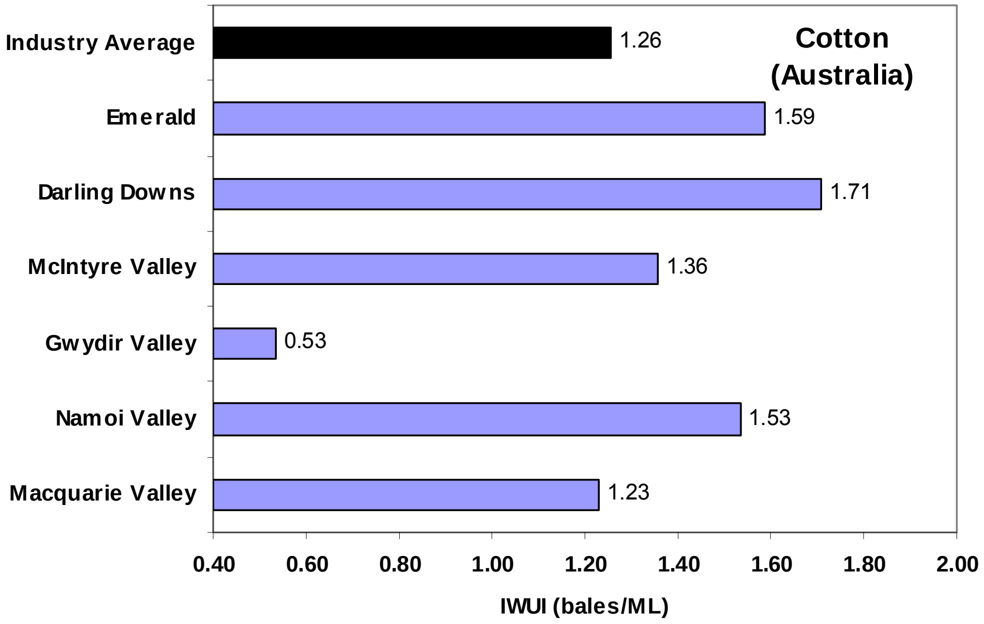


Figure 44. Irrigation Water Use Index (IWUI=Lint yield /Irrigation) obtained in the different cotton producing valleys in Queensland and New South Wales, Australia. Adapted from average values reported in Table 4 of Tennakoon and Milroy (2003). The Australian cotton industry average is highlighted.

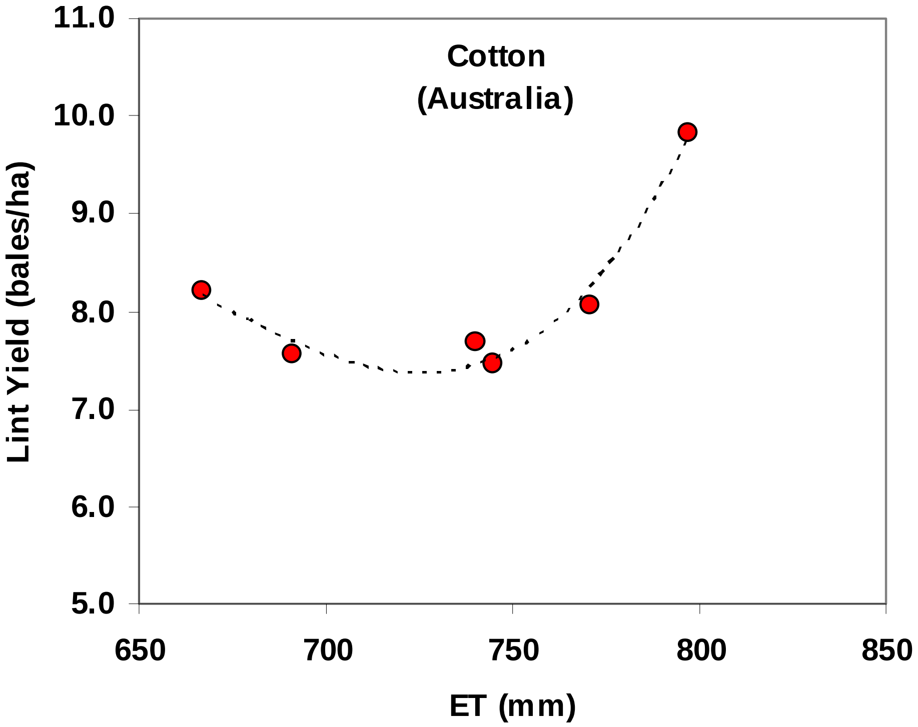


Figure 45. Lint yield as a function of evapotranspiration (ET). Data obtained in the different cotton producing valleys in Queensland and New South Wales, Australia. Adapted from average values reported in Table 3 of Tennakoon and Milroy (2003).

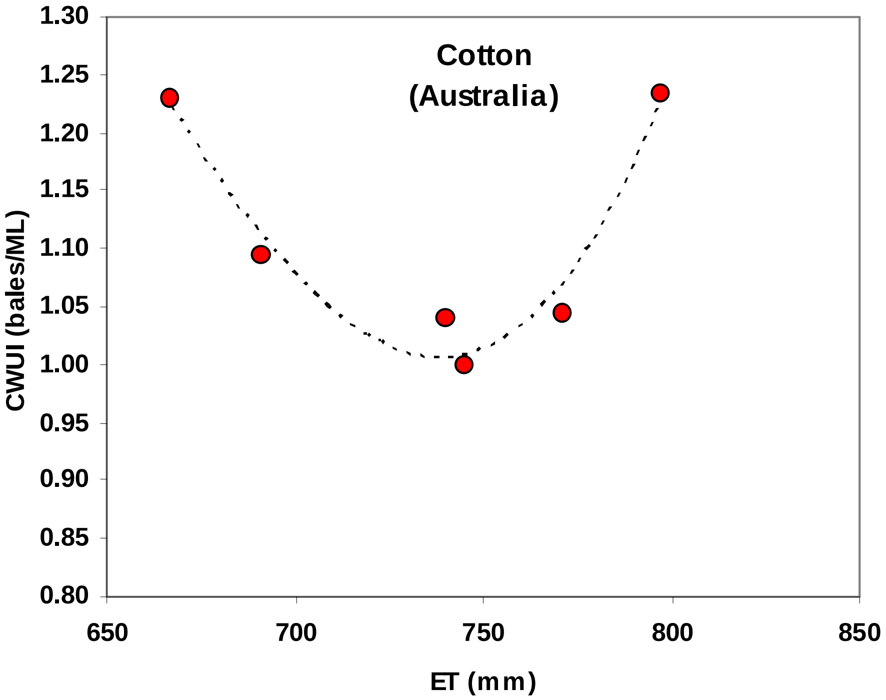


Figure 46. Crop water use Index (CWUI=Lint yield /ET) as a function of evapotranspiration (ET). Data obtained in the different cotton producing valleys in Queensland and New South Wales, Australia. Adapted from average values reported in Table 3 of Tennakoon and Milroy (2003).

Economic WUE from the Cotton Comparative Analysis

This comparative analysis report was produced by a join initiative between the Cotton Catchment Communities CRC, the Cotton Research and Development Corporation (CRDC) and Boyce Chartered Accountants (Newnham et al., 2006). The purpose was to produce the industry benchmark for the economics of cotton grown in Australia. In addition to economic data, it presented information on relevant production data like yields, water use, and water use efficiency from 1996 to 2005. It also provided summary data for the “top 20% of farmers” and for the “low cost farmers.” The basic information for the report was obtained by surveying farmers who were clients of Boyce Chartered Accountants, and as such was not strictly a random survey. By contacting the authors of the report (Newnham et al., 2006), data summarised by valleys were obtained (Table 22). The report has the shortcoming that it does not include data for all cotton producing valleys. It only provides data for the Gwydir, Macquarie, Namoi, Emerald, Walgett/Bourke, and McIntyre/Barwon areas.

According to this report, participants in this survey have grown cotton on an average of 816 ha/farm, with considerable variations among years and valleys. The average total water use (rain + irrigation) was estimated at 8.55 ML/ha, which represented a total of 7110 ML/farm. The total water use in this report is much lower than the 12 ML/ha reported by Tennakoon and Milroy (2003). Also, this report did not show the large amounts of total water use reported by Tennakoon and Milroy (2003) for the Gwydir Valley, which begs the question of which of the two sources is correct.

These farmers produced an average lint yield of 8.15 bales/ha, practically the same as the 8.13 bales/ha reported by Tennakoon and Milroy (2003). The top 20% of farmers produced 9.23 bales/ha, which shows the potential for farmers to still increase yields. Average yields were considerably higher in 2005, compared to previous years, with 10.03 bales/ha.

The report did not provide irrigation or evapotranspiration data, therefore it was not possible to calculate the CWUI or the IWUI, and it was only possible to calculate the GPWUI (yield/total water). The GPWUI, based on the total water use (rain + irrigation), averaged 0.98 bales/ML of total water. Valley data ranged from 0.76-1.04 bales/ML, and the top 20% of farmers achieved 1.10 bales/ML. The average GPWUI for all farms was higher than the 0.74 bales/ML reported by Tennakoon and Milroy (2003), but lower than the 1.25 bales/ML obtained from the crop competition data in the Darling Downs.

Economic indicators per ML of total water (rain + irrigation) included gross return and operating profit. Gross return, which averaged $660/ML in 2004 dropped to $480/ML in 2005, mainly as a result of lower cotton prices. The overall average for all farms and years was $453/ML. There were considerable variations among valleys, ranging from $295/ML in the Walgett/Bourke area to $501/ML in the Gwydir Valley. The highest gross return was obtained at the Gwydir Valley, which suggest looking closely at the low performance (high water use and low IWUI) suggested by the data of Tennakoon and Milroy (2003) for this valley.

Operating profits per ML of total water (rain + irrigation) for all farms and years averaged $99/ML, with higher profits for both the “top 20% of farmers” ($183/ML) and the “low cost farmers” ($147/ML). Despite the lower gross revenues due to low cotton prices, average profits per ML were higher in 2005 ($158/ML) compared with 2004 ($82/ML). This could be explained by a significant reduction in cost of production from $4,000/ha in 2004 to $2,949/ha in 2005, a reduction of $1051/ha. A closer look at the cost of production figures reported for 2005 compared to 2004 revealed a decrease in the use of chemicals, which could be explained by a change from conventional varieties to Bollgard cotton and, with the low cotton prices, farmers also found ways to decrease cost in other areas (Newnham et al., 2006). The greatest average profits per unit water ($116/ML) were obtained in the McIntyre/Barwon area, followed by the Gwydir Valley ($110/ML). The lowest average profits per unit water were obtained in the Walgett/Bourke area (-$23/ML), due to losses carried over from 2003(-$276/ML), despite obtaining good profits in 2005 ($195/ML).

Table 22. Summary from the Australian Cotton Comparative Analysis-2005 crop (Newnham et al., 2006).

Cotton area grown per farm (ha/farm)

Years	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	Average
All Farms		651	763	880	1006	941	1039	535	498	1028	**816**
Top 20% of Farmers		744	972	846	1031	1173	1041	498	690	830	**869**
Low Cost Farmers		569	1004	839	1017	1050	746	721	505	1394	**872**
Gwydir			862	856	1133	1565	1462	771	717	1064	**1054**
Macquarie			620	751	1050	1132	1063	435	392	522	**746**
Namoi			260	825	989	491	562	562	336	1230	**657**
Emerald			0	0	860	622	1225	1433	295	0	**554**
Walgett/Bourke			0	0	0	0	357	65	0	429	**106**
McIntyre/Barwon			815	964	1095	988	1254	472	487	1187	**908**

Total water use (rain + irrigation) per unit area (ML/ha)

Years	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	Average
All Farms		8.38	8.19	8.14	9.48	9.43	9.29	8.14	6.93	9.00	**8.55**
Top 20% of Farmers		7.66	7.49	8.14	8.89	9.02	9.47	9.13	7.14	10.00	**8.55**
Low Cost Farmers		6.79	8.12	7.83	8.91	9.13	7.33	8.55	7.17	10.54	**8.26**
Gwydir			8.48	8.30	9.38	10.49	9.29	8.13	6.40	7.78	**8.53**
Macquarie			8.57	7.66	10.57	9.11	9.35	8.98	6.97	17.92	**9.89**
Namoi			6.76	8.55	8.15	8.49	7.06	7.06	6.85	9.82	**7.84**
Emerald					9.54	7.72	9.84	10.04	6.78		**8.78**
Walgett/Bourke							13.23	8.35		9.91	**10.50**
McIntyre/Barwon			8.14	8.20	9.46	10.03	9.35	7.32	7.31	8.64	**8.56**

Total water use (rain + irrigation) per farm (ML/Farm)

Years	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	Average
All Farms		5456	6247	7163	9537	8878	9653	4354	3452	9249	**7110**
Top 20% of Farmers		5695	7280	6883	9169	10583	9855	4544	4925	8300	**7470**
Low Cost Farmers		3861	8155	6570	9059	9584	5470	6160	3623	14693	**7464**
Gwydir			7310	7106	10627	16419	13581	6268	4589	8277	**9272**
Macquarie			5314	5750	11101	10309	9935	3908	2734	9359	**7301**
Namoi			1756	7053	8061	4168	3966	3966	2301	12075	**5418**
Emerald					8209	4802	12057	14387	2000		**8291**
Walgett/Bourke							4727	543		4246	**3172**
McIntyre/Barwon			6634	7904	10359	9909	11725	3454	3562	10252	**7975**

Cotton Lint yield (bales/ha)

Years	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	Average
All Farms	7.04	8.07	8.41	6.98	8.08	7.90	8.41	8.10	8.45	10.03	**8.15**
Top 20% of Farmers	8.24	8.72	9.03	7.85	9.58	8.83	9.72	9.88	8.81	11.66	**9.23**
Low Cost Farmers	6.64	8.37	8.52	7.13	8.85	7.97	6.84	7.87	8.55	9.67	**8.04**
Gwydir			8.53	6.37	9.33	7.82	9.15	8.71	9.07	10.37	**8.67**
Macquarie			7.97	7.16	6.61	7.93	7.48	8.70	8.22	8.01	**7.76**
Namoi			8.42	6.96	6.71	7.59	8.08	8.08	7.92	10.60	**8.04**
Emerald					8.18	8.39	7.73	5.42	8.84		**7.71**
Walgett/Bourke							7.03	6.02		10.09	**7.71**
McIntyre/Barwon			8.80	7.23	9.20	7.95	9.26	8.29	8.11	9.84	**8.58**

Gross Production Water Use Index (GPWUI) [(Lint yield/(rain + irrigation)] (bales/ML)

Years	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	Average
All Farms		0.98	1.03	0.85	0.85	0.84	0.91	0.99	1.22	1.11	**0.98**
Top 20% of Farmers		1.14	1.2	0.96	1.08	0.98	1.03	1.09	1.23	1.16	**1.10**
Low Cost Farmers		1.18	1.05	0.91	0.99	0.87	0.93	0.92	1.19	0.92	**1.00**
Gwydir			1.01	0.77	0.99	0.75	0.98	1.08	1.41	1.33	**1.04**
Macquarie			0.93	0.93	0.63	0.87	0.80	0.97	1.18	0.45	**0.84**
Namoi			1.25	0.81	0.83	0.89	1.15	1.15	1.16	1.08	**1.04**
Emerald					0.85	1.09	0.79	0.54	1.30		**0.91**
Walgett/Bourke							0.53	0.72		1.02	**0.76**
McIntyre/Barwon			1.08	0.88	0.97	0.79	0.99	1.14	1.11	1.14	**1.01**

Gross Return WUI [gross return/(rain + irrigation)] ($/ML)

Years	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	Average
All Farms		$440	$489	$397	$365	$368	$384	$491	$660	$480	**$453**
Top 20% of Farmers		$542	$564	$485	$484	$439	$391	$538	$648	$470	**$507**
Low Cost Farmers		$571	$498	$407	$433	$372	$394	$427	$637	$383	**$458**
Gwydir			$488	$379	$451	$348	$453	$549	$746	$590	**$501**
Macquarie			$435	$423	$273	$386	$332	$450	$662	$179	**$392**
Namoi			$602	$370	$336	$387	$506	$506	$637	$461	**$476**
Emerald					$353	$408	$319	$187	$1,003		**$454**
Walgett/Bourke							$199	$248		$438	**$295**
McIntyre/Barwon			$508	$409	$401	$343	$389	$582	$582	$484	**$462**

Operating Profit WUI [operating profit/(rain+irrigation)] ($/ML)

Years	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	Average
All Farms		$150	$166	$38	$76	$67	$82	$73	$82	$158	**$99**
Top 20% of Farmers		$236	$249	$128	$184	$143	$118	$184	$173	$228	**$183**
Low Cost Farmers		$240	$214	$72	$157	$107	$88	$76	$186	$181	**$147**
Gwydir			$163	$14	$141	$59	$123	$121	$107	$151	**$110**
Macquarie			$117	$28	$15	$84	$15	$81	$66	$34	**$55**
Namoi			$183	$19	$1	$70	$148	$148	$51	$126	**$93**
Emerald					$57	$34	$49	-$88	$150		**$41**
Walgett/Bourke							$12	-$276		$195	**-$23**
McIntyre/Barwon			$195	$69	$129	$59	$113	$93	$71	$201	**$116**

WUE from Cotton Grower Survey (Doyle and Coleman, 2007)

Doyle and Coleman (2007) estimated WUE values for different cotton producing regions for the 2005-06 season as shown in Fig. 47A. WUE values averaged 1.73 bales/ML, ranging from 1.29 for the southern region to 2.29 for the northern region. In this study, however, it is difficult to know exactly what WUE mean, since some growers included rainfall in the calculation of WUE and other did not. Figure 47B shows that the percentage of farmers including rainfall in the calculation of WUE varied widely by region. On average for all regions, less than half (48%) of the growers included rainfall in the calculation, but the values varied from 15% for the Namoi region to 76.5 % for the Border Rivers/Gwydir/St. George region. Including or not including rainfall in the calculation of WUE are both correct, as long as the information is reported with the correct water use index, instead of using the generic WUE. In this study, since data with and without rainfall were mixed together, the WUE values are very difficult to interpret.

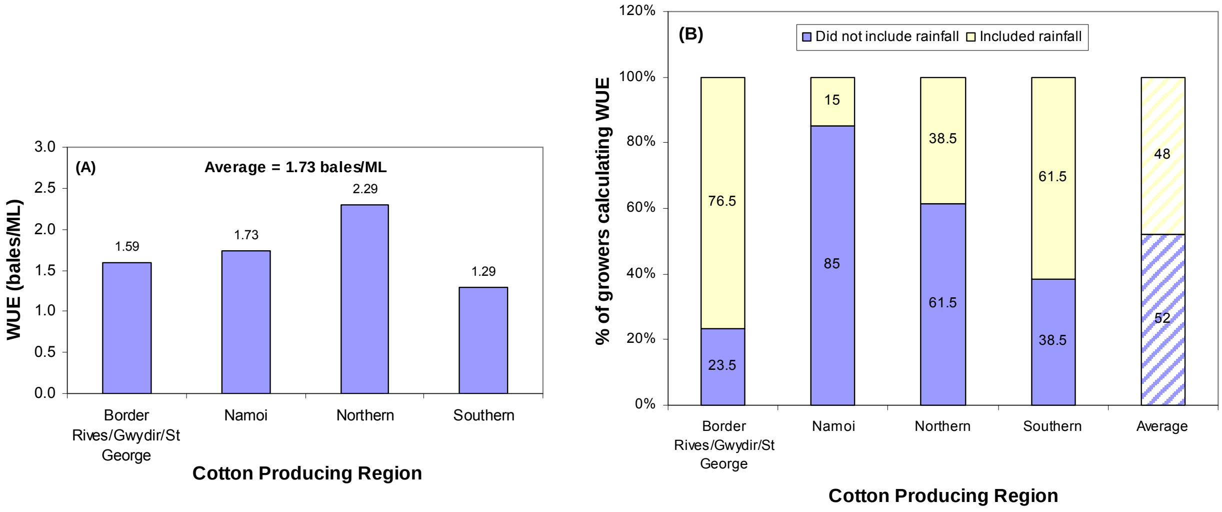


Figure 47. Results of a survey with cotton growers for the 2005-06 season conducted by Doyle and Coleman (2007). (A) Water use efficiency (WUE) by region, and (B) % of growers surveyed that included or did not include rainfall in their calculation of WUE.

Australian Field Water Use Efficiency Data

Darling Downs Crop Competitions

To estimate cotton WUE from actual farmer's fields, data from crop competitions on the Darling Downs, which include some entries from the Lockyer Valley, were obtained. These competitions are sponsored by the Royal Agricultural Society of Queensland (RASQ) and the Darling Downs Cotton Growers Inc. This dataset has the advantage that it includes a period of 19 years (1987 to 2005) which could provide information about seasonal tendencies. On the other hand, it has the disadvantage that the information was supplied by farmers by filling up a form, which makes it difficult to ascertain data quality. Therefore, it is expected that some of the information provided by farmers was actually measured while other was just estimated. Also, since data were supplied as part of a yield competition, only farmers obtaining the best yields would have entered the competition. Data, therefore, are not expected to be representative of average farmers, but represent the best farmers in the area. As such, they provide an indication of what is actually possible for normal commercial operations in the area.

For analysis, only entries with complete records were used. An entry was considered complete if it provided information on yield, irrigation amount or number of irrigations, and in-crop rainfall. In cases where only the number of irrigation was provided, the amount of irrigation was estimated by assuming that each irrigation was equal to 1 ML/ha (100 mm), which is a common estimate used by surface-irrigators in the area (Goyne et al., 2000). The number of complete entries included in the analysis varied considerably from year to year (Figure 48). A total of 204 complete entries were analysed, including 23 dryland and 181 irrigated entries. Dryland entries for cotton are only available since 2000.

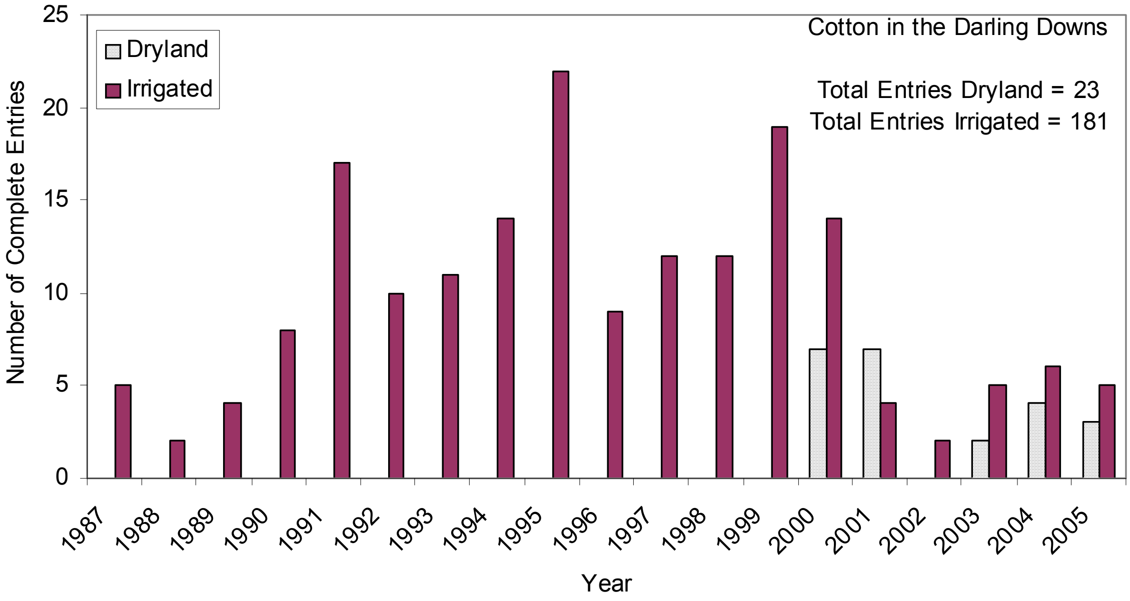


Figure 48 Number of complete entries for farmers participating in cotton yield competitions in the Darling Downs, Australia. An entry was considered complete if it provided information on yield, number of irrigations, and in-crop rain.

Results indicate that irrigation amounts, dryland yields, and WUE indices were affected by in-crop rainfall. The average in-crop rainfall reported by farmers during the 1987-2005 period was 4.23 ML/ha (423 mm), with significant variability from year to year, ranging from approximately 250 mm in 1993, 1997, 2003, and 2005 to more than 650 mm in 1996 (Figure 49).

Irrigation amounts and number of irrigations varied considerably from year to year (Figures 50 and 51). On average, farmers reported applying 3.4 irrigations (including pre-irrigation), representing an average of approximately 3.5 ML/ha. Figure 50 shows that although the number of irrigations tended to decrease with in-crop rainfall, the relationship had several outliers that suggest the influence of other factors, such as lack of water to satisfy crop water demands, inappropriate irrigation scheduling, occurrence of sudden storms that farmers could not anticipate, etc.

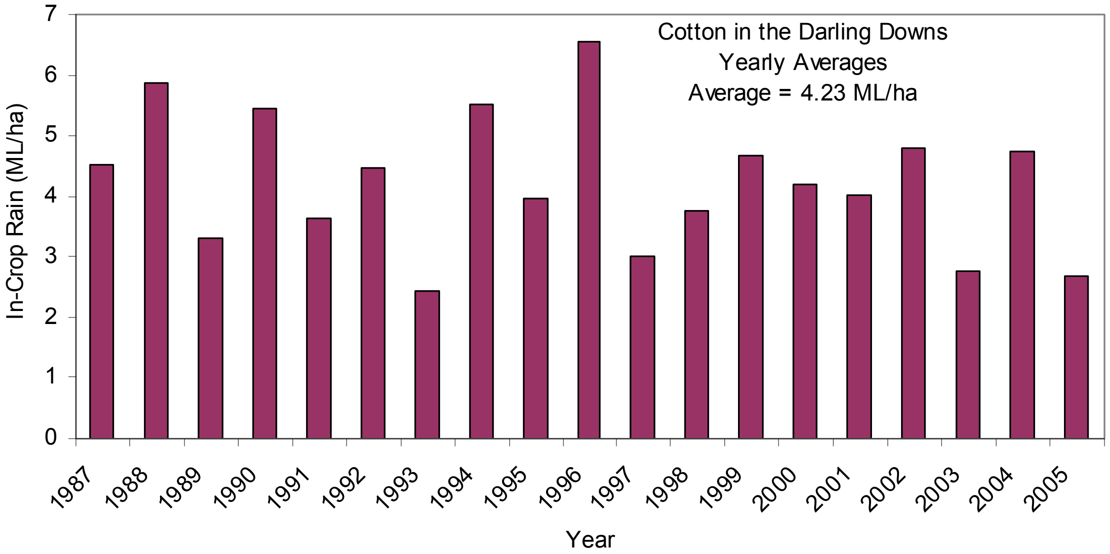


Figure 49. Average in-crop rain for cotton by year, reported by farmers participating in yield competitions in the Darling Downs, Australia.

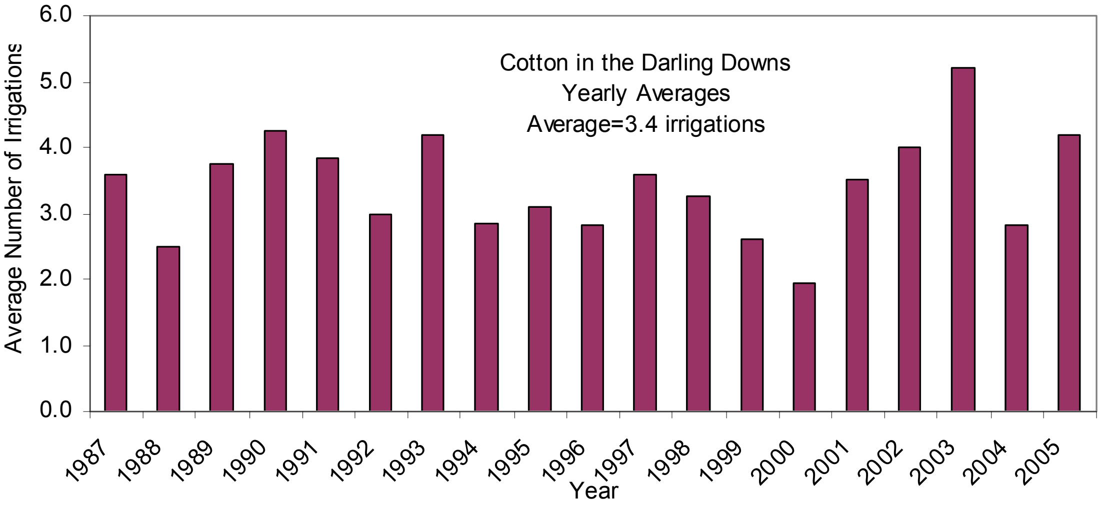


Figure 50. Average number of irrigations for cotton by year, applied by farmers participating in yield competitions in the Darling Downs, Australia.

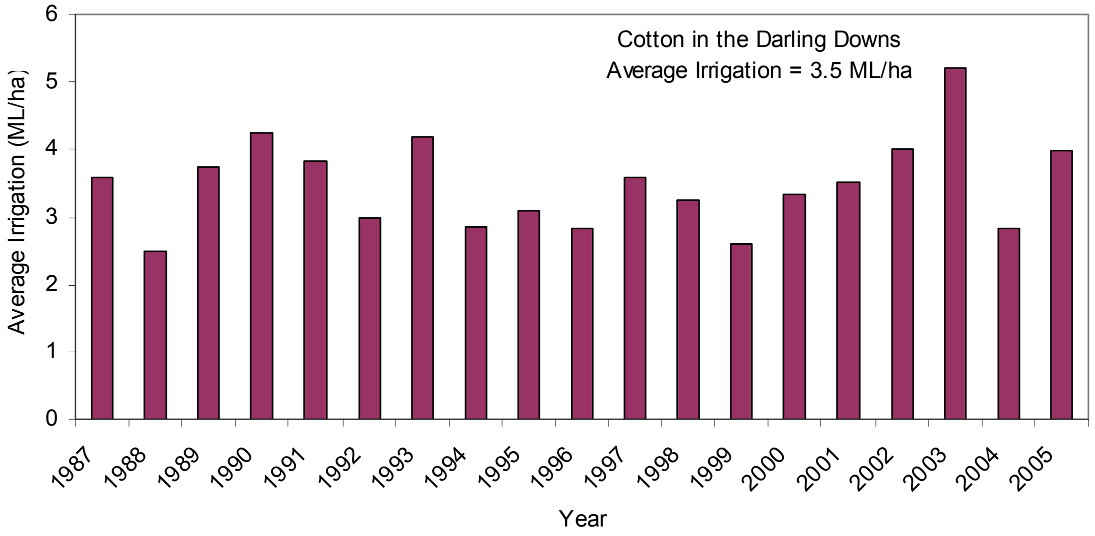


Figure 51. Average irrigation amount for cotton by year, reported by farmers participating in yield competitions in the Darling Downs, Australia.

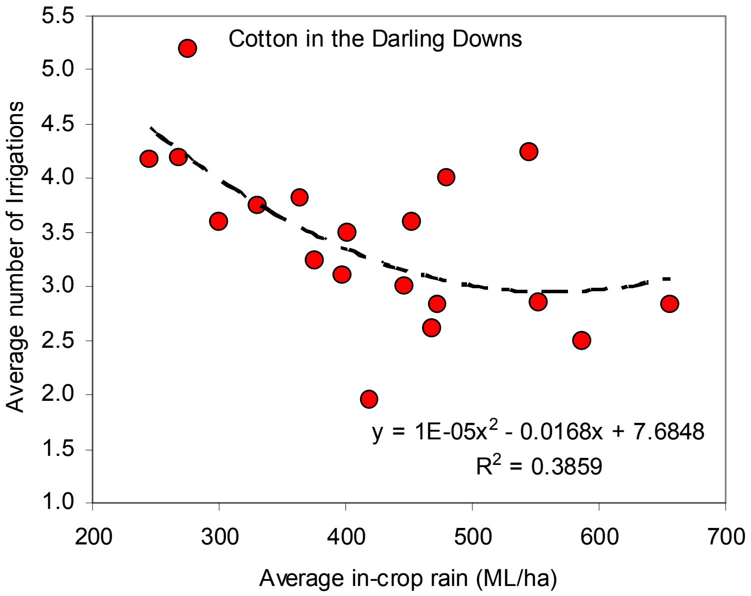


Figure 52 Average number of irrigations as a function of average in-crop rain for cotton, obtained from data provided by farmers participating in yield competitions in the Darling Downs, Australia, from 1987-2005.

Total water inputs (rain + irrigation) averaged 7.7 ML/ha (770 mm), but have been steadily decreasing since 2002 (Figure 53). This decrease could be due to increasing restriction in water supplies, to improved water management, or to a combination of both.

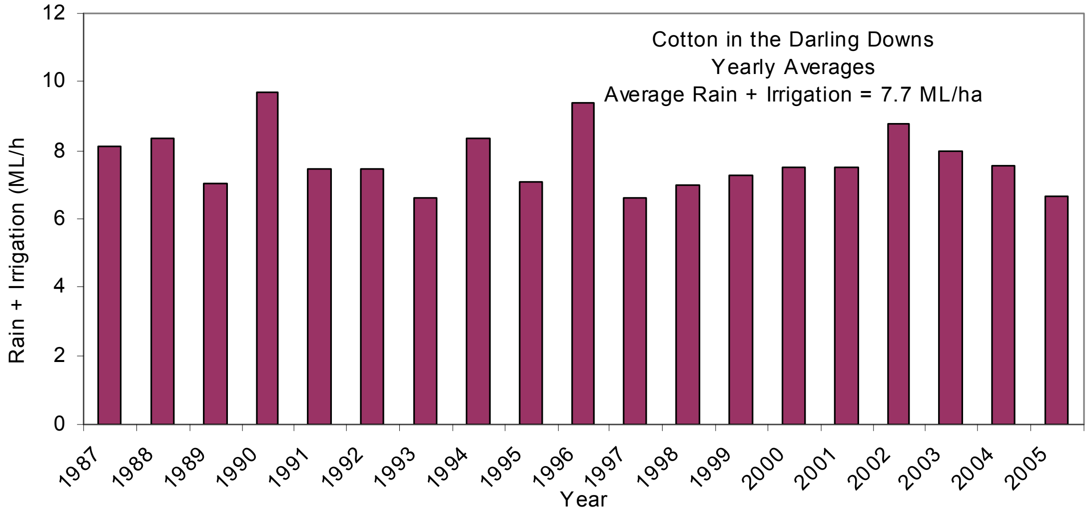


Figure 53. Average total water (rain + irrigation) for cotton by year, reported by farmers participating in yield competitions in the Darling Downs, Australia.

Lint yields show considerable variation from year to year, with an average of 9.34 bales/ha for irrigated and 4.83 bales/ha for dryland cotton (Fig. 54). Irrigated yields peaked in 2001, and have tended to steadily decrease in the last 5 years, which could be related to the decrease in water inputs (rain + irrigation) discussed above. Figure 55 suggests that on average for all years, lint yield tended to increase for (rain + Irrigation) ≤ 7.0 ML/ha, but limited yield increases resulted from additional water inputs. These results suggest that 7.0 ML/ha of (rain + irrigation) are enough to meet the crop water requirements and reach the yield potential in the area during most seasons. It could also mean that other yield limiting factors are present at higher water input levels.

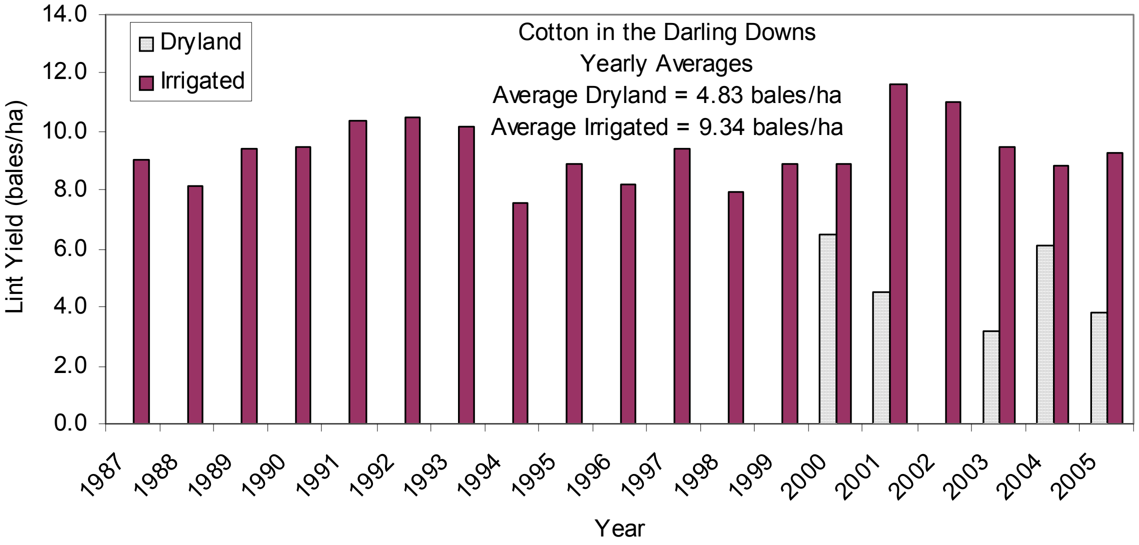


Figure 54. Average cotton lint yields by year, reported by farmers participating in yield competitions in the Darling Downs, Australia.

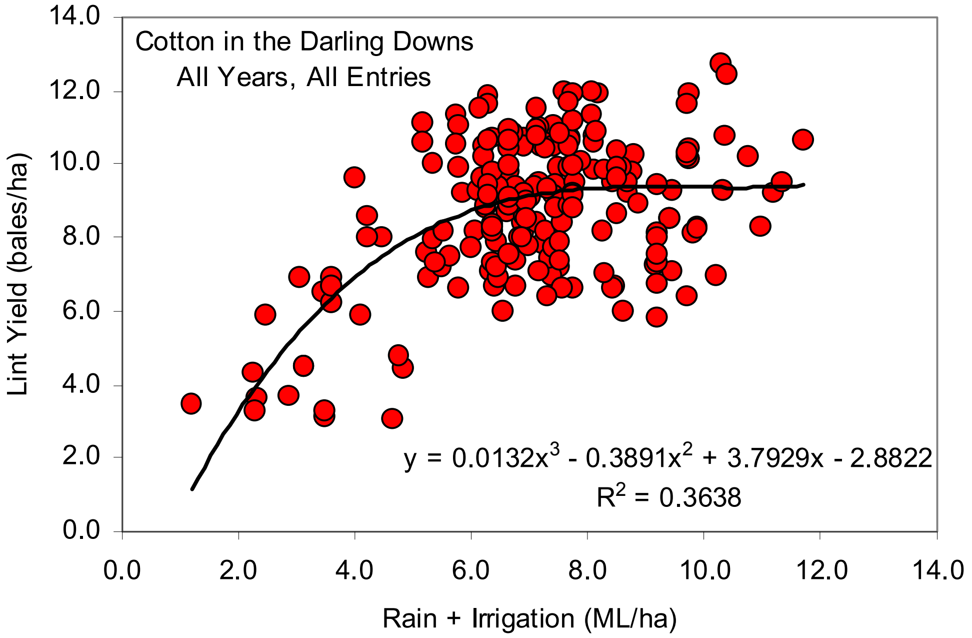


Figure 55 Cotton lint yield as a function of total water (rain + irrigation), obtained from data provided by farmers participating in yield competitions in the Darling Downs, Australia, from 1987-2005.

Water use efficiencies were calculated as gross production water use index [GPWUI=lint yield/ (rain +irrigation)] and also as irrigation water use index [IWUI = lint yield/ irrigation]. Since ET data were not available, the crop water use index [CWUI (lint yield/ET)] could not be calculated from this dataset. The GPWUI averaged 1.25 bales/ML for irrigated and 1.59 for dryland cropping systems, respectively (Figure 56). The GPWUI tended to decrease with the amount of (rain + Irrigation) (Figure 57). This decreasing trend suggests that in this area a positive dryland yield could be obtained even when (rain + irrigation) = 0, just relying on stored soil water at sowing.

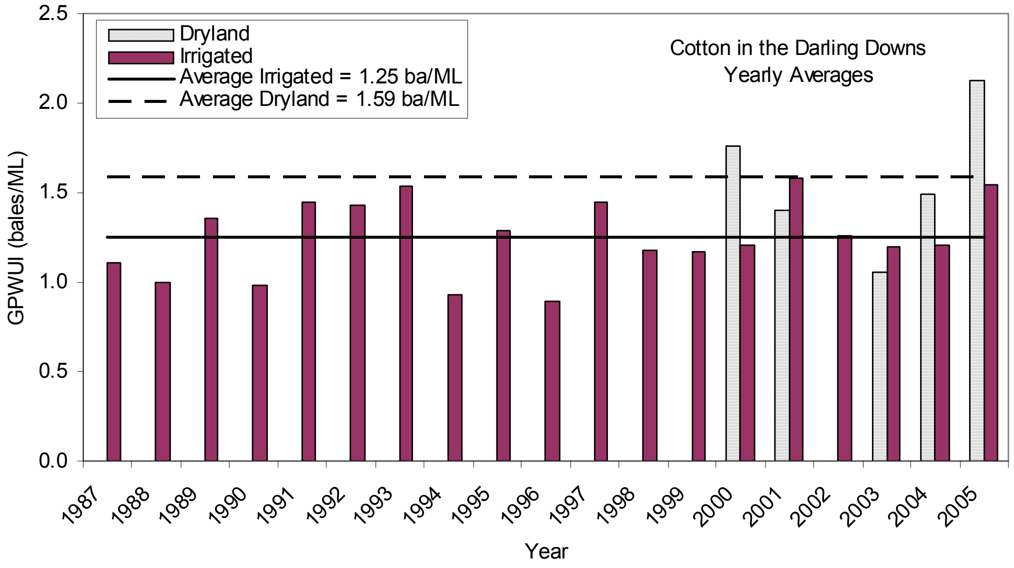


Figure 56 Average gross production water use index [GPWUI = (Lint yield)/(rain + irrigation)] for cotton by year, calculated from data provided by farmers participating in yield competitions in the Darling Downs, Australia.

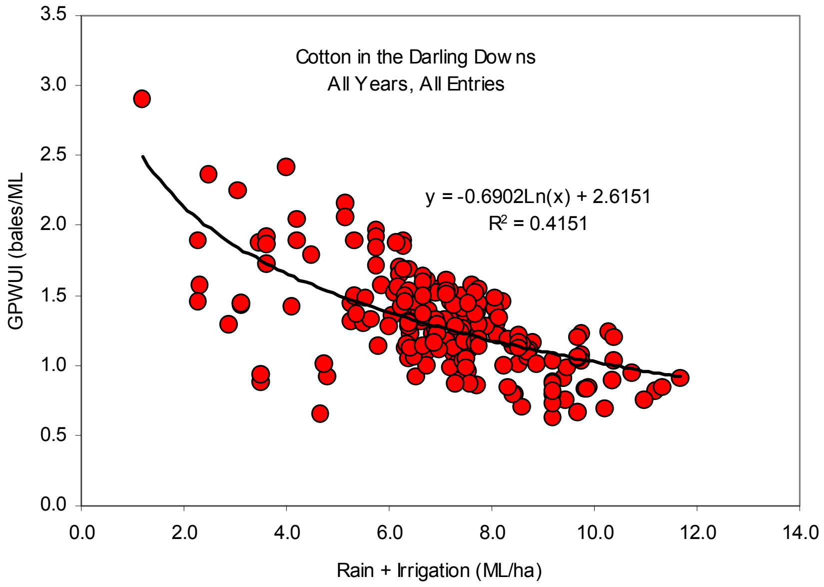


Figure 57. Gross production water use index [GPWUI = (Lint yield)/(rain + irrigation)] as a function of (rain + irrigation) for cotton, obtained from data provided by farmers participating in yield competitions in the Darling Downs, Australia, from 1987-2005

The IWUI values obtained by growers entering the competitions averaged 2.75 bales/ML of irrigation during the 1987-2005 period (Figure 58). These are very high values, indicating that in this area it is quite possible to reach the industry goal of increasing the industry average to 2.0 bales/ML of irrigation. The IWUI for individual entries, however, was well-related to irrigation and also tended to decrease with irrigation amount, ranging from around 2 to 12 bales/ML of irrigation (Figure 59). This wide range is not surprising given the sensitivity of the IWUI to in-crop rainfall and to irrigation amount discussed earlier. These values suggest that very high values are possible in wet years and/or in areas requiring little irrigation. For years requiring more than 3 ML/ha of irrigation the IWUI tended to level off at a value of approximately 2.0 bales/ML. The decreasing pattern of IWUI with irrigation follows the theory for areas and seasons with a positive dryland yield discussed earlier. Therefore, in this area IWUI can be increased by decreasing irrigation, even when the crop is stressed. That, of course, will reduce yields, total production, and will also reduce the CWUI. The effect of deficit irrigation on economic gross margins per unit area ($/ha), irrigation ($/ML) and at the whole-farm ($/farm) levels are discussed later in this report.

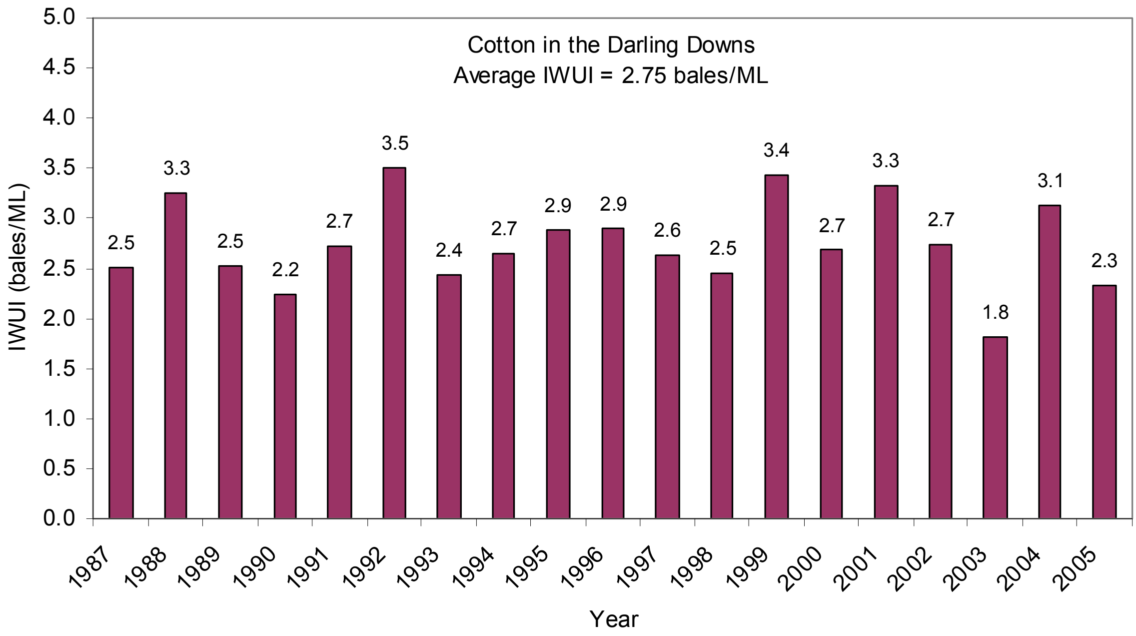


Figure 58 Average irrigation water use index (IWUI =lint yied/irrigation) for cotton by year, calculated from data provided by farmers participating in yield competitions in the Darling Downs, Australia.

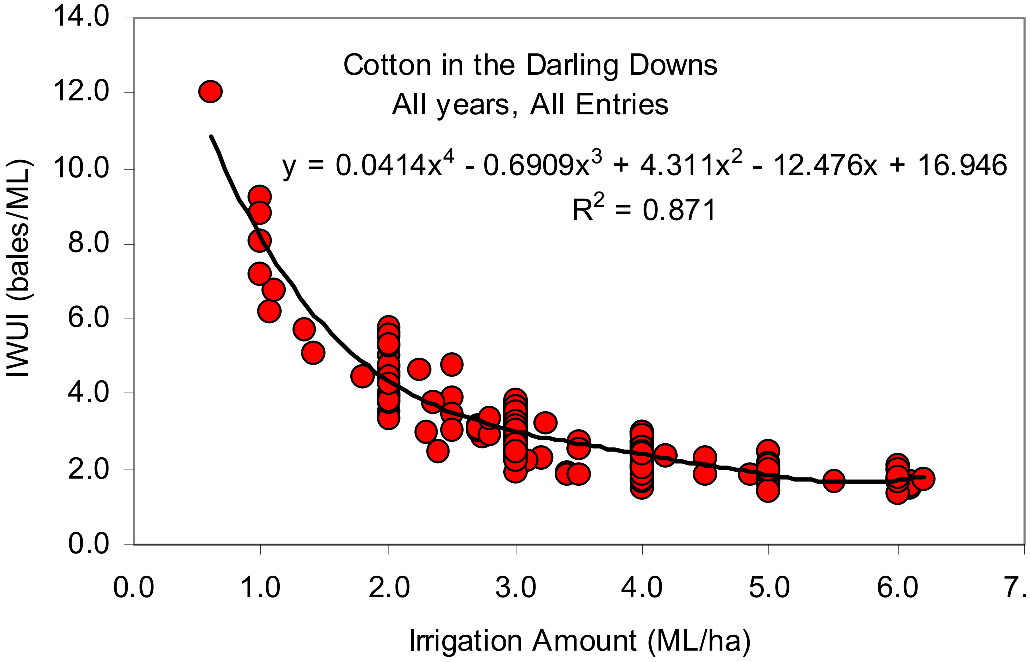


Figure 59 Irrigation water use index (IWUI = lint yield/irrigation) as a function of irrigation amount for cotton, obtained from data provided by farmers participating in yield competitions in the Darling Downs, Australia, from 1987-2005

Historical WUE data from farm in the Namoi Valley

Figure 60 shows historical water use efficiency values obtained for a farm in the Namoi valley from the 1991-02 to the 2005-06 season (name not given to keep confidentiality). The farm manager calculated the indices in different ways, by including either the water sources pre and post planting or by only including the water sources post planting (Figures A and B). Figure 60 shows considerably seasonal variability in the indices, with much more seasonal variability for the IWUI compared to the GPWUI. In this dataset, soil water was not considered in the calculations of the WUE indices. They also compared WUE values between a furrow and a lateral move system in 2005-06 and found higher GPWUI and IWUI with the lateral move system as shown in Fig. 61.

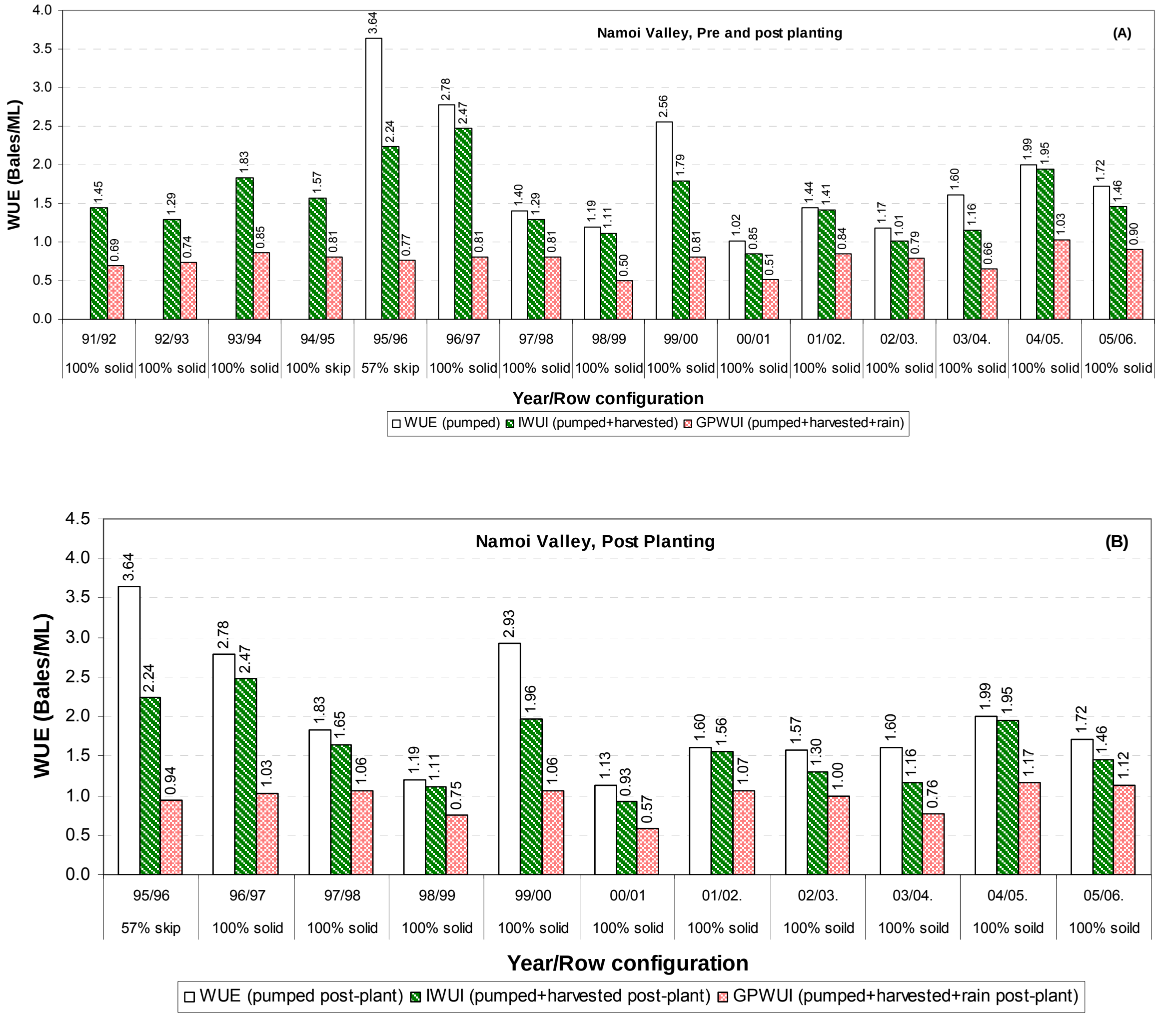


Figure 60 Water use efficiency values obtained on a farm in the Namoi Valley, Australia, from the 1991-02 to the 2005-06 season. The terms “solid” and “skip” are the row configurations. (A) includes total water applied pre and post planting, and (B) only includes water applied post planting. IWUI =irrigation water use index (yield/irrigation), GPWUI =gross production water use index (yield/ total water). In the legends, the sources of water used to calculate the water use index are indicated in parenthesis.

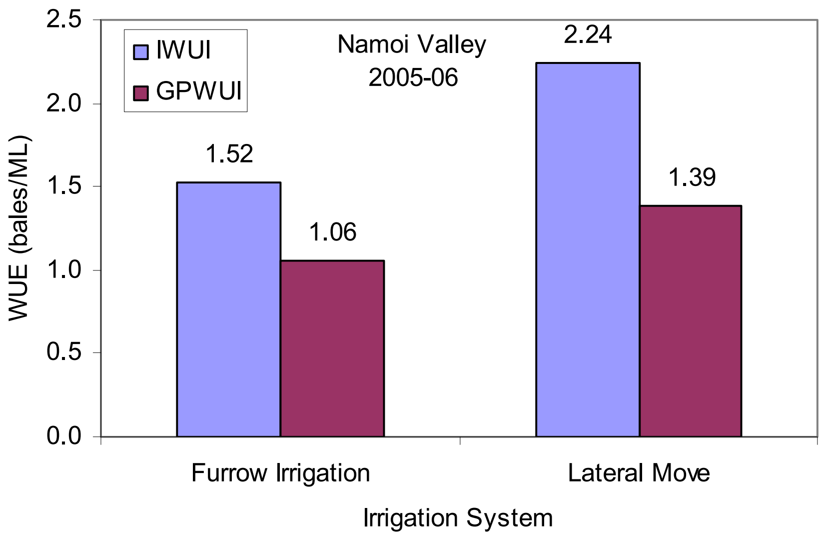


Figure 61 Water use efficiency values obtained with furrow and lateral move irrigation systems in a farm in the Namoi Valley, Australia, during the 2005-06 season. IWUI =irrigation water use index (yield/irrigation), GPWUI =gross production water use index (yield/ total water).

Historical WUE data from a Grower at four locations in the Gwydir Valley

Figure 62 shows historical water use efficiency values obtained by a grower at four locations in the Gwydir Valley from the 1999-00 to 2005-06 (name not given to keep confidentiality). It shows that considerable variability in the indices occurred among locations within the same year and also among years for the same location.

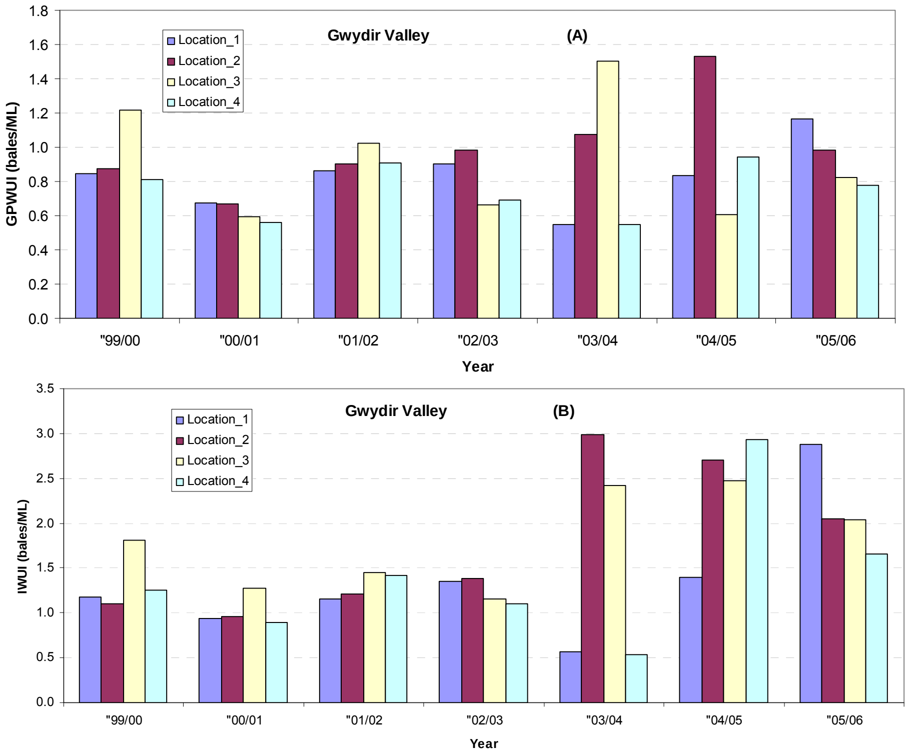


Figure 62 Water use efficiency values obtained by a farmer at four different locations in the Gwydir Valley, Australia, from the 1999-00 to the 2005-06 season. IWUI =irrigation water use index (yield/irrigation), GPWUI =gross production water use index (yield/ total water).

WUE data from the Rural Water Use Efficiency Initiative (RWUEI): Cotton and Grain Adoption Program

The RWUEI was conducted in Queensland from July 1999 to June 2003 with the objectives of:

- Increasing irrigation efficiency in the cotton and grain industries by a least 10% and,
- Have 70% of growers adopting best management practice guidelines for irrigation, which were developed during the program.

At the start of the RWUEI, a stocktake study (Goyne et al., 2000) was conducted to be taken as a baseline to evaluate the impact of the project. They estimated water use efficiencies for cotton based on a desktop study, and from crop competition data obtained on the Darling Downs and the Lockyer Valley for the period of 1987-1999. The desktop study included analysis of data from farm surveys on the Darling Downs, McIntyre valley, and Emerald, combined with the application of a water balance model to estimate ET and CWUI (lint yield/ET). The desktop study resulted in an overall average CWUI of 1.11 bales per ML of estimated evapotranspiration (Table 23). The higher CWUI values were obtained for the Darling Downs, which could be due to its low ET values compared to the other regions, as discussed earlier. The lowest CWUI were obtained for the McIntyre Valley, which has a higher ET compared to the Darling Downs.

Table 23. Estimated Crop water use index (CWUI = lint yield/ET) (bales/ML of ET) for cotton for three regions in Australia. Adapted from results of desktop study reported in Table 3 of Goyne et al. (2000).

Region	No. farms	1996/97	1997/98	1998/99	Average
Darling Downs	3		1.19	1.27	1.23
McIntyre	1	1.08	1.02	0.99	1.01
Emerald	5		1.12	1.08	1.10
Average					**1.11**

Since the crop competition data did not provide enough information to obtain an accurate estimate of ET, Goyne et al. (2000) had to make several assumptions to be able to estimate some of the components of the water balance, including the assumption that all water received by the crop was equal to ET. The estimated CWUI values based on these assumptions are shown in Table 24 for cotton and grain crops. The CWUI values for cotton obtained with this dataset (1.18 bales/ML of estimated ET) was similar to the 1.23 bales/ML obtained for the Darling Downs using the desktop study (Table 23). A wide range of CWUI values (0.8-1.5 bales/ML), however, was obtained. This wide range indicates the variability among farming operations included in the analysis and the difficulty in obtaining a meaningful industry average.

Table 24. Crop Water Use Index (CWUI = yield/ET) for cotton and grain crops estimated from crop competition data collected in the Darling Downs and the Lockyer Valley from 1987-1999. Adapted from results reported in Table 4 of Goyne et al. (2000).

Crop	Average	Range
Grain crops	----------- t/ML -----------	
Sorghum	1.54	1.1-2.2
Soybean	0.52	0.4-0.8
Sunflower	0.59	0.4-0.8
Barley	2.25	1.2-3.7
Maize	1.94	1.2-4.5
Wheat	2.32	1.0-2.5
	----------- bales/ML -----------	
Cotton	1.18	0.8-1.5

Although the RWUEI was not a research project, but focussed on extension, it included a series of trials and field demonstrations in all the cotton producing areas of Queensland, which resulted in WUE data. Results of the project have been described in detail in several milestone reports (Goyne, 2003; Goyne, 2002; Goyne and McIntyre, 2000; Goyne and McIntyre, 2001; Goyne and McIntyre, 2006; Goyne et al., 2000). A summary of the WUE values for cotton obtained in field trials during 2000/01 to 2002/03 in the different valleys in Queensland are shown in Table 25. The crop water use indices in this study varied with season and location with no consistent tendency. The state average CWUI for cotton was 1.28 bales/ML of ET, which was about 15% higher than the value estimated during the stocktake study at the start of the project.

Combining all data obtained during the RWUEI project resulted in the relationships shown in Fig. 63. It shows that in this study, the irrigation water use index (IWUI) and the irrigation economic water use index (IEWUI) were both well related with net irrigation, decreasing as net irrigation increased. These results suggest potential benefits of implementing irrigation practices that reduce net irrigation (such as deficit irrigation) both in terms of water savings and economics. These results also suggest that in some instances, dryland production could be more profitable than irrigated agriculture. Figure 63 also shows that in this study the CWUI tended to decrease with evapotranspiration, which seems to contradict the increasing trend suggested previously. The apparent contradiction, however, is not such because the increasing trend should hold for data collected at only one location. When mixing data from different locations, such in this case, it is expected that the location with the higher ET will have the lower CWUI, assuming that the yield potential does not change with location. Therefore, when mixing data from different locations, a decreasing CWUI trend with ET as observed in this dataset seems very reasonable. Figure 63 also shows that the GPWUI was poorly related to total water, although a slightly tendency to increase with total water was observed.

Table 25. Water use indices resulting from cotton field trials conducted under the Rural Water Use Efficiency Initiative (RWUEI) during 2000/01 to 2002/03 in different valleys in Queensland. Adapted from Goyne (2003).

Location/Season	Gross Irrigation	Net Irrigation	Total Rain	Effective Rain	Total Water	ET	Lint Yield	CWUI	IWUI	GPWUI	IEWUI ($450/bale)	IEWUI ($550/bale)	Application Efficiency	Irrigation Efficiency
	|-----------------------------------	ML/ha		--------------------------------			(bales/ha)	|-------------	bales/ML	-------------|	|---------$/ML	-------------|	|-------------	% -------------
St. George														
2000/01	9.90	6.70	3.30	1.60	8.30	7.20	8.60	1.19	1.28	1.04	$ 578	$ 706	68	
2001/02	8.90	6.90	2.10	1.50	8.40	8.30	10.70	1.29	1.55	1.27	$ 698	$ 853	78	50
2002/03	11.70	7.80	1.40	1.10	8.90	7.20	8.70	1.21	1.12	0.98	$ 502	$ 613	67	68
Average	***10.17***	***7.13***	***2.27***	***1.40***	***8.53***	***7.57***	***9.33***	***1.23***	***1.31***	***1.09***	***$ 589***	***$ 720***	***70***	***59***
Border Rivers														
2000/01	10.20	6.52	4.68	1.60	8.12	8.37	9.00	1.08	1.38	1.11	$ 621	$ 759	64	
2001/02	8.01	5.19	2.06	1.94	7.13	6.80	8.79	1.29	1.69	1.23	$ 762	$ 932	65	74
2002/03	7.55	6.28	1.44	1.25	7.53	6.80	9.10	1.34	1.45	1.21	$ 652	$ 797	83	
Average	***8.59***	***6.00***	***2.73***	***1.60***	***7.59***	***7.32***	***8.96***	***1.22***	***1.49***	***1.18***	***$ 673***	***$ 822***	***70***	***74***
Darling Downs														
2000/01	6.20	4.90	3.60	2.80	7.70	7.20	8.40	1.17	1.71	1.09	$ 771	$ 943	79	
2001/02	5.13	4.44	3.95	2.70	7.14	7.45	10.70	1.44	2.41	1.50	$ 1,084	$ 1,325	87	
2002/03	4.33	3.41	5.39	2.74	6.15		8.70	.	2.55	1.41	$ 1,148	$ 1,403	79	
Average	***5.22***	***4.25***	***4.31***	***2.75***	***7.00***	***7.33***	***9.27***	***1.30***	***2.18***	***1.32***	***$ 981***	***$ 1,199***	***81***	
Dawson/Callide														
2000/01	7.10	5.30	3.80	2.60	7.90	7.20	8.00	1.11	1.51	1.01	$ 679	$ 830	75	
2001/02	5.60	4.20	3.50	2.80	7.00	8.00	8.10	1.01	1.93	1.16	$ 868	$ 1,061	75	
2002/03	5.90	4.40	3.40	1.70	6.10		6.33		1.44	1.04	$ 647	$ 791	75	
Average	***6.20***	***4.63***	***3.57***	***2.37***	***7.00***	***7.60***	***7.48***	***1.06***	***1.61***	***1.07***	***$ 726***	***$ 888***	***75***	
Emerald/Mackenzie														
2000/01	6.20	5.10	4.34	1.57	6.67		8.50		1.67	1.27	$ 750	$ 917	82	
2001/02	9.69	7.69		1.30	8.99	6.10	9.50	1.56	1.24	1.06	$ 556	$ 679	79	50
2002/03	6.20	5.60	1.30	0.60	6.20	6.30	7.50	1.19	1.34	1.21	$ 603	$ 737	90	
Average	***7.36***	***6.13***	***2.82***	***1.16***	***7.29***	***6.20***	***8.50***	***1.37***	***1.39***	***1.17***	***$ 624***	***$ 763***	***83***	***50***
Average for state														
2000/01	7.92	5.70	3.94	2.03	7.74	7.49	8.50	1.13*	1.49	1.11	$ 671	$ 820	72	60
2001/02	7.47	5.68	2.32	2.05	7.73	7.33	9.56	1.31	1.68	1.24	$ 757	$ 925	76	58
2002/03	7.14	5.50	2.59	1.48	6.98	6.77	8.07	1.25	1.47	1.16	$ 660	$ 807	77	
Overall Average	***7.51***	***5.63***	***2.95***	***1.85***	***7.48***	***7.20***	***8.71***	***1.28***	***1.55***	***1.17***	***$ 696***	***$ 851***	***75***	***59***

Total water = Net irrigation + effective rainfall, CWUI= crop water use index (yield/ET), IWUI = Irrigation water use index (yield/net irrigation)
GPWUI = Gross production water use index (yield/Total water), IEWUI = irrigation economic water use index (gross production ($/ha)/net irrigation(ML/ha))
Application Efficiency = 100 x (Net irrigation/Gross irrigation)
Irrigation Efficiency = 100 x [ET/(Total irrigation water inputs at the farm level available during the season)]
*These averages for state indices were listed as in the original source and were not recalculated from the data given in this table, which could result in different values.

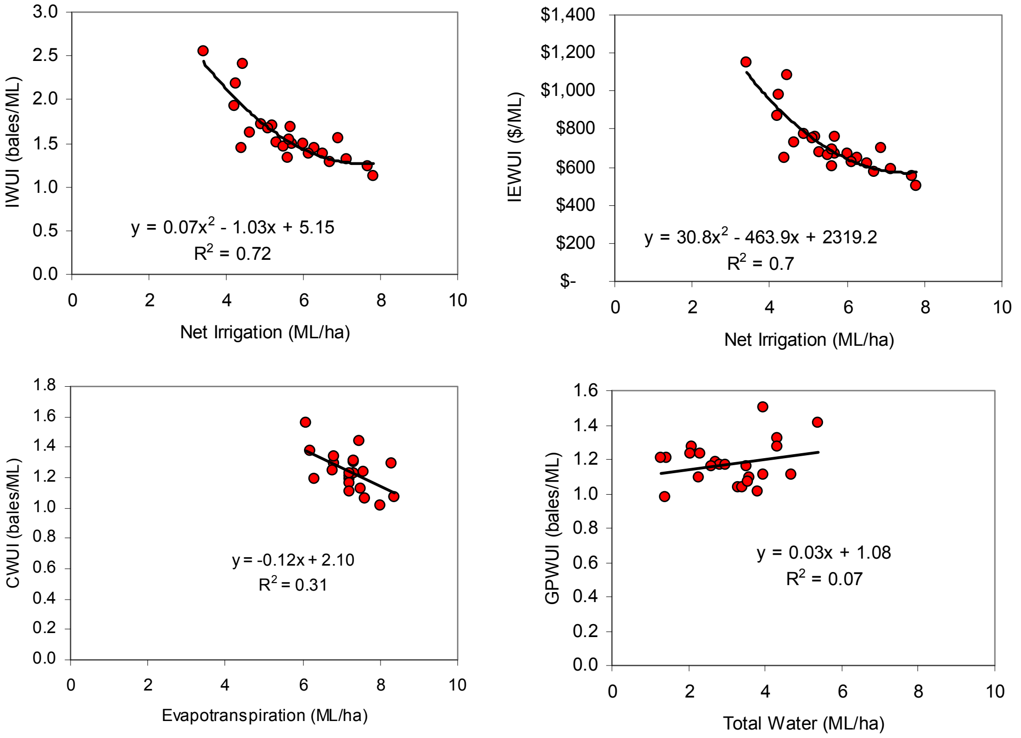


Figure 63. Relationships obtained in cotton field trials conducted under the Rural Water Use Efficiency Initiative (RWUEI) during 2000/01 to 2002/03 in different valleys in Queensland (data reported in Goyne, 2003). IWUI = Irrigation water use index (yield/net irrigation), and IEWUI = irrigation economic water use index (gross production ($/ha)/net irrigation (ML/ha)), CWUI =crop water use index (Yield/Evapotranspiration), GPWUI = Gross production water use index (Yield/Total Water).

WUE from alternative irrigation systems in Australia

Data from farmer's fields comparing IWUI from alternative irrigation systems in Australia have been reported by Raine and Foley (2002). They estimated cotton IWUI values by surveying farmers using different irrigation systems. They reported average and range IWUI values for subsurface drip irrigation (SDI), traditional furrow, and large mobile irrigation machines (LMIMs – centre pivots and lateral moves) (Table 26).

Table 26. Irrigation water use index (bales/ML of irrigation) values for different irrigation systems obtained from farmer's survey conducted by Raine and Foley (2002).

	Irrigation System		
	SDI	Traditional Furrow	LMIMs
Range	1.5-2.75*	0.6-1.6	1.35-2.6
Average	2.4*	1.0*	1.9

SDI = Subsurface drip irrigation, LMIMs = lateral move irrigation machines
*Values estimated from Fig. 1 of Raine and Foley (2002).

Since IWUI can vary significantly from year to year, IWUI values always need to be interpreted with caution. However, they should serve the purpose of comparing the performance of irrigation systems. As expected, the range of values was very wide for all irrigation systems. Also, as expected, the highest average IWUI was obtained with SDI, followed by the LMIMs, and the lowest with the traditional furrow system. This order reflects the potential irrigation efficiencies that can be achieved with the different irrigation systems, with the more efficient irrigation systems having the higher IWUI values. It is good to notice that changing from traditional furrow to LMIMs almost doubled the IWUI, and changing to SDI produced an additional increase in IWUI of almost 150% over traditional furrow. Although this improvement could probably be achieved in practice, the question is if it is feasible to change to more efficient irrigation systems. Factors to consider should not only be their water-saving potential, lower labour requirements, low environmental impact, potential for higher yield from reduced waterlogging, but also their high initial investment. The industry should also consider that some improvements can still be made by optimising traditional furrow irrigation systems, and also by improving irrigation scheduling.

The IWUI value for traditional furrow (1.0 bales/ML) reported in this study is lower than the 1.26 bales/ML obtained by Tennakoon and Milroy (2003). Also, it is interesting to notice that the IWUI values for all irrigation systems are lower than those obtained from the crop competition data in the Darling Downs, which use predominantly traditional furrow, and still averaged 2.75 bales/ML of irrigation.

WUE from commercial SDI and furrow systems:

Data comparing cotton IWUI and GPWUI from subsurface drip irrigation (SDI) and furrow irrigation systems from commercial fields at Biloela, and from demonstration fields at Dalby and Moree were reported by Harris (2005) (Table 27). In general, the SDI resulted in higher IWUI and GPWUI values by increasing yields, reducing water use, or both. On average for all site-years, the IWUI for SDI was 2.67 bales/ML compared to 1.51 bales/ML for the furrow system. This represented a 77% increase in IWUI by using SDI instead of the furrow system. The GPWUI was 1.39 bales/ML for SDI and 0.95 bales/ML for the furrow system, which represented a 46% increase in GPWUI with SDI over furrow.

Table 27. Comparison of cotton irrigated with subsurface drip irrigation and furrow irrigation from commercial (Biloela) and demonstration (Dalby and Moree) fields (Adapted from Harris, 2005).

			Subsurface Drip					Furrow Irrigation				
Site	Grower	Year	Yield (bales/ha)	Irrigation (ML/ha)	Rain (ML/ha)	IWUI (bales/ML)	GPWUI (bales/ML)	Yield (bales/ha)	Irrigation (ML/ha)	Rain (ML/ha)	IWUI (bales/ML)	GPWUI (bales/ML)
Biloela	B	95-96	10.13	4.69	4.30	2.16	1.13	8.40	5.68	4.30	1.48	0.84
	C	95-96	8.65	2.17	4.30	3.99	1.34	8.65	5.43	4.30	1.59	0.89
	B	96-97	9.26	3.71	3.64	2.50	1.26	8.89	5.19	3.64	1.71	1.01
	B	96-97	10.32	3.71	3.64	2.78	1.40	8.89	5.19	3.64	1.71	1.01
Dalby		2000-01	10.00	4.50	3.96	2.22	1.18	7.98	5.30	3.96	1.51	0.86
		2001-02	8.78	4.20	4.40	2.09	1.02	8.20	5.60	4.40	1.46	0.82
		2002-03	10.10	2.90	6.08	3.48	1.12	9.80	5.60	6.08	1.75	0.84
Moree		2000-01	7.36	3.73	1.50	1.97	1.41	7.80	6.00	1.50	1.30	1.04
		2001-02	7.42	3.29	1.84	2.26	1.45	6.80	5.85	1.84	1.16	0.88
		2002-03	8.37	2.60	0.62	3.22	2.60	10.18	7.27	0.62	1.40	1.29
Averages:												
Biloela			9.59	3.57	3.97	2.86	1.28	8.71	5.37	3.97	1.62	0.94
Dalby			9.63	3.87	4.81	2.60	1.11	8.66	5.50	4.81	1.57	0.84
Moree			7.72	3.21	1.32	2.48	1.82	8.26	6.37	1.32	1.29	1.07
Overall Average			9.04	3.55	3.43	**2.67**	**1.39**	8.56	5.71	3.43	**1.51**	**0.95**

Another comparison of furrow and SDI for cotton production was conducted in a replicated trial in a farmer's field in the Namoi Valley (Anonymous, No date). The results in Table 27 show for the first and second season, respectively, 25.2% and 30.2% less water was used with the SDI system compared to furrow. Since yields were similar for the two systems (within 6%), the lower irrigation application with SDI increased IWUI by 26.0% and 46.3% compared to furrow, for the first and second season, respectively. They attributed the water savings with SDI to more flexible irrigation scheduling after rain events, and to substantial water losses by deep drainage with the furrow system, suggested by analysis of Environscan data.

Although SDI performed better in terms of water savings and IWUI, their economic analysis showed that much higher economic returns were obtained with the furrow system during the two seasons, since SDI required significant investment compared to an existing furrow system. For the economic analysis they estimated the cost of a large-scale SDI system at about $4800/ha, including about 1/3 of the total cost for drip lines and the other 2/3 for plumbing and filtration of river water. They also assumed that SDI water savings could be used to increase SDI-irrigated area, an interest rate of 10% on SDI invested capital, a life span of 10 years for drip lines and 15 years other SDI component, 100% cotton rotation, a general crop production cost of $2,500/ha, and cotton prices for 1996/97 and 1997/98 of $480 and $440/bales, respectively. In their analysis, however, they did not consider the potential labour savings of SDI, and while a high cost was assumed for SDI, the existing furrow system was assumed to have no cost at all.

Table 28 Comparison of furrow and subsurface drip irrigation systems for cotton production in the Namoi Valley, Australia (Anonymous, No date).

Year	Variable	Furrow Irrigation	Subsurface Drip	Difference (%)
1996/97	Yield (bales/ha)	7.63	7.20	-5.6%
	Irrigation (ML/ha)	2.58	1.93	-25.2%
	IWUI (bales/ML)	2.96	3.73	26.0%
	Return ($/ha)	$1,149	$93	-91.9%
1997/98	Yield (bales/ha)	9.79	9.98	1.9%
	Irrigation (ML/ha)	7.18	5.01	-30.2%
	IWUI (bales/ML)	1.36	1.99	46.3%
	Return ($/ha)	$1,832	$1,062	-42.0%

WUE from alternative management of furrow irrigation systems

Vaschina (2001) compared three alternative management options for a furrow irrigation system in a field in Macalister for one season. Results in Table 29 show that they obtained an increase in IWUI from 1.50 to 1.80 bales/ML by using “single syphon/alternate furrow” instead of “single syphon/every furrow.” Since yields were the same with both management options, the increase was due to a reduction in irrigation amount from 7.00 to 5.83 ML/ha, a reduction of 1.17 ML/ha. This was a big reduction in water use, especially considering that at the time, the average gross return was $800/ML and a water savings of 1.17 ML/ha could return $936/ha. Although this was only data from one site-year, it shows the kind of management improvements that can be made at the field level to increase IWUI. These gross returns are much higher than those from the Boyce report for the same period, since they are gross returns per unit of irrigation while those in the Boyce report are per unit of total water (rain + irrigation).

Yields in this study averaged 10.67 bales/ha, which were higher that the average from the crop competition data in the Darling Downs (9.34 bales/ha). Despite the higher yields, the average IWUI in this study was much lower than the average obtained from the crop competition data in the Darling Downs (2.75 bales/ML). This was due to more irrigation applied in this study (6.57 ML/ha) compared to the crop competition average (3.5 ML/ha).

Table 29. Results from alternative management of a furrow irrigation system in a cotton field at Macalister, Australia. Adapted from data reported in Tables 1 and 2 of Vaschina (2001). IE=irrigation efficiency, IWUI =irrigation water use index (lint yield/irrigation).

Plot	IE (%)	Yield (bales/ha)	Yield (kg/ha)	Irrigation (ML/ha)	IWUI (bales/ML)	IWUI (kg/ha/mm)	Gross Return ($/ML)
Single Syphon/Alternate Furrow	78	10.50	2384	5.83	1.80	4.09	$882
Double Syphon/Alternate Furrow	64	11.00	2497	6.88	1.60	3.63	$784
Single Syphon/Every Furrow	73	10.50	2384	7.00	1.50	3.41	$735
Average	**72**	**10.67**	**2421**	**6.57**	**1.63**	**3.71**	**$800**

WUE from furrows and siphon-less irrigation systems

During the 2005/06 season, Hood and Carrigan (2006) compared GPWUI values from four “siphon-less” systems with adjacent furrow-irrigated fields. The four “siphon-less” systems included overhead irrigation (lateral move), “bank-less channel,” “bank-less head ditch,” and “pipes through the banks” systems. Water balance data were collected from farmers fields located throughout the Border River and Lower Balonne catchments. Results in Table 30 show higher GPWUI values for the “Pipe through the bank” and lateral move system compared with furrow, while lower values were obtained with the “Bank-less channel” and “Bank-less head ditch” systems. GPWUI averaged 0.92 and 0.97 bales/ML of total water for the “siphon-less” and furrow systems, respectively. The GPWUI ranged from 0.45 to 1.30 bales/ML for the “siphon-less” systems, and from 0.78 to 1.11 bales/ML for the furrow system. Overall, the highest value was obtained with the lateral move system, and the lower value with the “Bank-less head ditch” system.

Table 30 Gross production water use index (GPWUI =lint yield/total water) for cotton obtained with “siphon-less” and furrow irrigation systems. Adapted from Hood and Carrigan (2006).

“Siphon-less” system	**GPWUI (bales/ML)**	
	“Siphon-less”	**Furrow**
Bank-less Channel	1.06	1.11
Bank-less head ditch	0.45	1.06
Pipe through the bank	0.88	0.78
Lateral move	1.30	0.93
Average	**0.92**	**0.97**

WUE reported in WATERpak

In one of the Australian cotton industry irrigation extension materials (WATERpack), Tennakoon et al.(2004) summarized cotton water use efficiency values obtained in Australia during the previous fifteen years, which included values obtained by three projects (Cameron and Hearn, 1997; Rural Water Use Efficiency Initiative, 2003) (Table 31). In this summary, the CWUI, IWUI, and GPWUI averaged 1.23, 1.32, and 0.85 bales/ML of ET, irrigation, and total water, respectively. This table shows yield increases from 6.73 bales/ha in the late 1980’s to 8.73 bales/ML in 2003. However, irrigation has also increased from 5.37 ML/ha to 7.51 ML/ha over the same period. Therefore, the IWUI tended to decrease from 1.48 to 1.16 bales/ML of irrigation.

Table 31 Cotton water use efficiency estimated by three projects for the Australian cotton industry from the 1988/89 to 2002/03 period (Adapted from Tennakoon et al., 2004).

Project	Seasons	State	No. of Farms	Irrigation (ML/ha)	Total Water (ML/ha)	Seasonal ET (mm)	Lint Yield (bales/ha)	IWUI (farm) (bales/ML)	GPWUI (farm) (bales/ML)	CWUI (kg/ha/mm)	CWUI (bales/ML)	WFIE (%)
Cameron & Hearn (1997)	88/89-94/95	NSW, Qld	11	5.37			6.73	1.48	0.82	3.05	1.34	63
CSIRO Plant Industry	96/97-98/99	NSW, Qld	25	6.96	12.1	735	8.13	1.32	0.79	2.52	1.11	57
RWUEI (2003)	00/01-02/03	Qld	29	7.51	9.36	721	8.73	1.16	0.93	2.79	1.23	58
Industry Average				**6.61**	**10.73**	**728**	**7.86**	**1.32**	**0.85**	**2.79**	**1.23**	**59**

WUE from different fields within the same farm

Figure 64 shows GPWUI and IWUI values obtained by a grower on the Darling Downs for different fields within the same farm during the 2005-06 season (name not given to keep confidentiality). Values include data obtained with lateral move, furrow, and dryland systems. They also include values from solid and skip row planting configurations. This dataset shows the variability in water use indices that can occur even within the same farm. The GPWUI averaged 1.32 bales/ML and ranged between 0.84 (Dryland) to 1.71 bales/ML. The IWUI averaged 3.68 bales/ML and ranged between 2.97 and 5.58 bales/ML. In this dataset, both the GPWUI and IWUI tended to be higher for the lateral move compared to furrow (for solid planting). For the furrow system, the skip-row system tended to have lower GPWUI, but higher IWUI compared to solid planting.

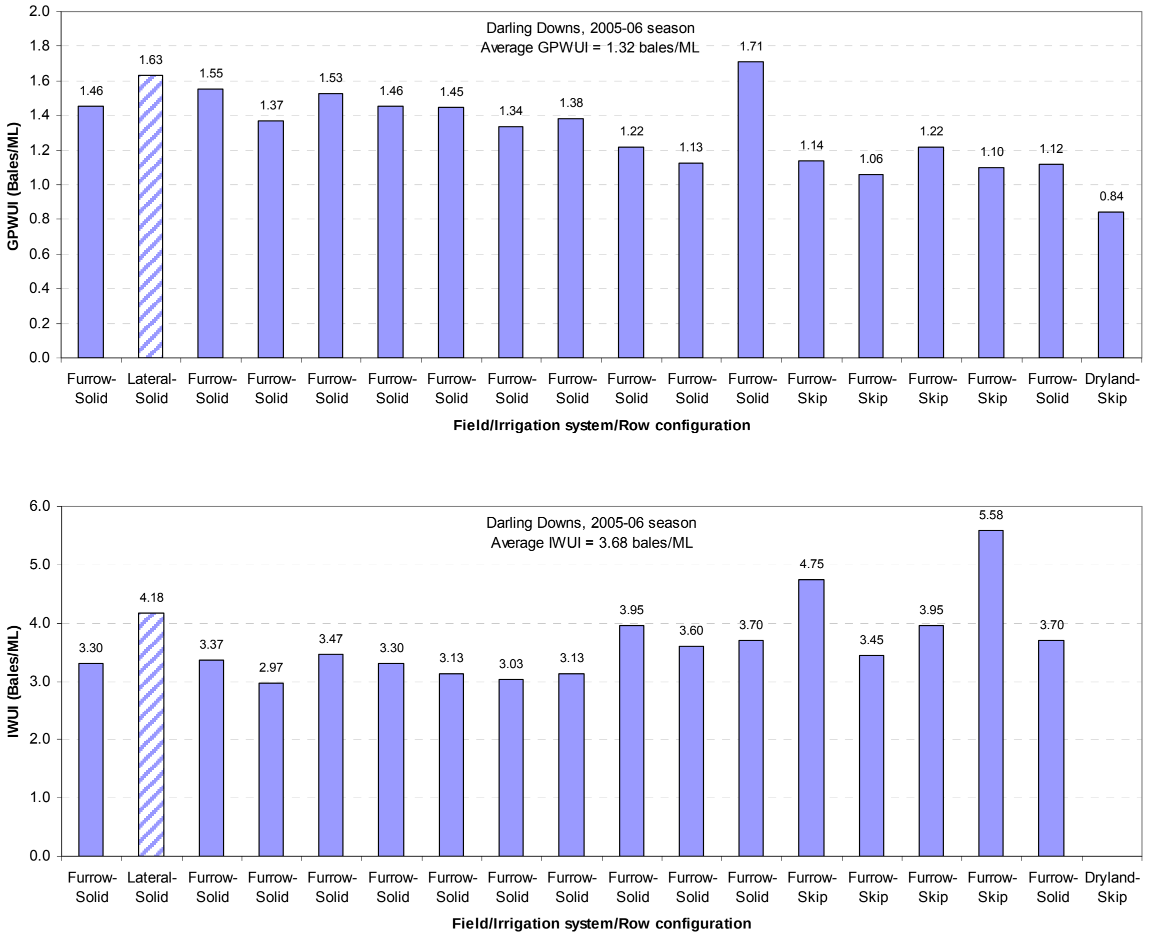


Figure 64 Gross production water use index (GPWUI=Yield/total water) and irrigation water use index (IWUI=Yield/Irrigation) values obtained in different fields within the same farm during the 2005-06 season on the Darling Downs. The values obtained with the lateral move are highlighted. “Lateral” means lateral move, and “solid” and “skip” are the row configurations.

WUE from Selected International Datasets

In this section, selected datasets of cotton water use efficiency values from around the world are presented as comparison to the values obtained in Australia.

WUE from the Farm and Ranch Irrigation Surveys in the USA

Table 32 shows the IWUI of cotton obtained with sprinkler and surface irrigation systems in different states in the USA. Data were derived from the 1998 and 2003 Farm and Ranch Irrigation Surveys conducted by the United States Department of Agriculture (USDA) (United States Department of Agriculture, 1999; United States Department of Agriculture, 2004). On average for all states for both 1998 and 2003, cotton yields were higher under surface than under sprinkler irrigation. However, a plot of the yield data (Figure 65) reveals that the apparent higher average yields with surface irrigation were driven by just three yield values, with all the other yields being comparable between the surface and sprinkler systems. Less water was applied with sprinkler compared to surface irrigation. Figure 66 shows that the amount of water applied with both systems (including all states in Table 32) were linearly related for both 1998 and 2003. The slope of the line shows that on average 23 and 25% more water was applied with the surface system for 1998 and 2003, respectively.

Table 32. Irrigation water use index (IWUI = lint yield/irrigation) of cotton obtained with sprinkler and surface irrigation systems in different states in the USA. Adapted from data reported in United States Department of Agriculture (1999 and 2004)

1998 Irrigation System and Cotton Performance	**Sprinkler**					**Surface**				
State	Farms	Area (ha)	Yield (bales/ha)	Irrigation Water Applied (ML/ha)	IWUI (bales/ML)	Farms	Area (ha)	Yield (bales/ha)	Irrigation Water Applied (ML/ha)	IWUI (bales/ML)
Alabama	68	4709	4.46	2.13	2.09					
Arizona	3	304	4.23	11.88	0.36	510	98208	5.85	14.6	0.40
Arkansas	153	56102	3.53	2.13	1.66	527	125488	3.78	2.1	1.77
California	47	22477	3.96	7.01	0.56	1561	238253	4.68	9.1	0.51
Florida	13	2390	2.83	2.44	1.16					
Georgia	854	94355	4.02	2.44	1.65					
Kansas										
Louisiana	70	15057	3.77	2.44	1.55	132	18527	3.01	2.4	1.24
Mississippi	161	33667	4.24	1.83	2.32	112	19408	4.22	1.8	2.31
Missouri	70	13351	2.67	1.83	1.46	152	24994	2.72	1.2	2.23
New Mexico	71	6779	4.75	6.70	0.71	207	14471	4.83	8.2	0.59
North Carolina	63	5227	4.37	1.83	2.39					
Oklahoma	18	585	1.99	3.66	0.55	118	19208	4.63	5.2	0.89
South Carolina	78	6329	4.17	1.83	2.28					
Tennessee	12	1326	3.66	1.22	3.00					
Texas	1634	315847	3.25	3.66	0.89	1046	184996	3.06	4.0	0.77
Virgina	11	200	4.09	2.44	1.68					
Total/Average	**3326**	**578704**	**3.75**	**3.47**	**1.52**	**4365**	**743553.04**	**4.09**	**5.42**	**1.19**

Source: USDA - 1998 Farm and Ranch Irrigation Survey

2003 Irrigation System and Cotton Performance	**Sprinkler**					**Surface**				
State	Farms	Area (ha)	Yield (bales/ha)	Irrigation Water Applied (ML/ha)	IWUI (bales/ML)	Farms	Area (ha)	Yield (bales/ha)	Irrigation Water Applied (ML/ha)	IWUI (bales/ML)
Alabama	53			2.44		0	0			
Arizona	12			9.44		429	83416	6.52	13.1	0.50
Arkansas	302	108943	4.51	1.83	2.47	492	147574	4.92	2.1	2.31
California	179	38777	5.99	8.23	0.73	1109	264697	6.68	8.8	0.76
Florida	14	3214	4.17	2.74	1.52	0				
Georgia	707	85439	4.91	1.22	4.03	29	7902	5.05	0.9	5.53
Kansas	46	12010	4.16	2.74	1.52	8	434	4.69	3.4	1.40
Louisiana	65	15270	5.40	1.83	2.95	373	46757	4.87	1.5	3.19
Mississippi	281	99647	5.17	1.52	3.39	233	73337	5.40	1.5	3.55
Missouri	200	42802	4.39	1.22	3.60	190	45240	4.70	1.8	2.57
New Mexico	152		5.08	5.79	0.88	109		5.46	8.2	0.66
North Carolina	64			0.91		2				
Oklahoma	71	6362	3.87	3.05	1.27	99	17763	6.04	3.7	1.65
South Carolina	29	3347		1.22		5	142		0.0	
Tennessee	16	3919	5.15	1.22	4.23	0				
Texas	2263	366238	3.63	2.74	1.32	946	120679	3.50	3.4	1.04
Virgina										
Total/Average	**4454**	**785967**	**4.70**	**3.01**	**2.33**	**4024**	**807942**	**5.26**	**4.04**	**2.11**

Source: USDA - 2003 Farm and Ranch Irrigation Survey

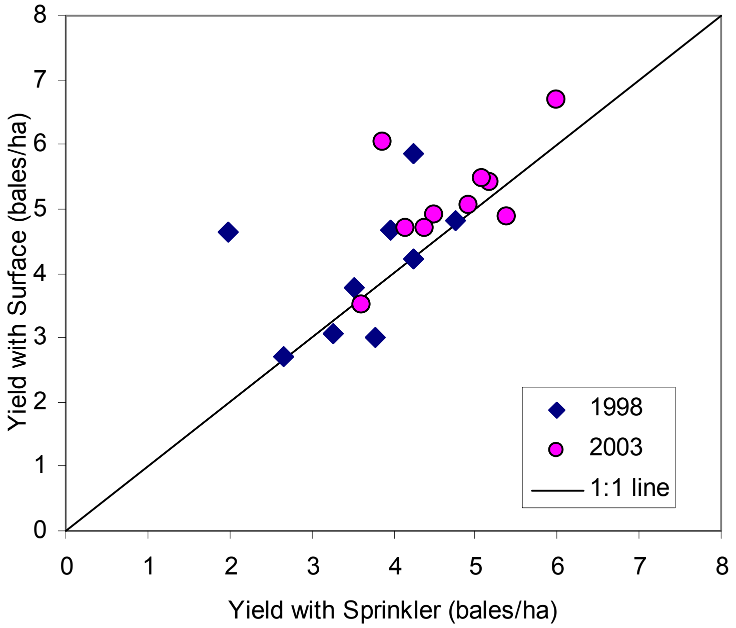


Figure 65 Relationships of cotton yields obtained with sprinkler and surface irrigation systems in the United States. Adapted from data reported in United States Department of Agriculture (1999 and 2004).

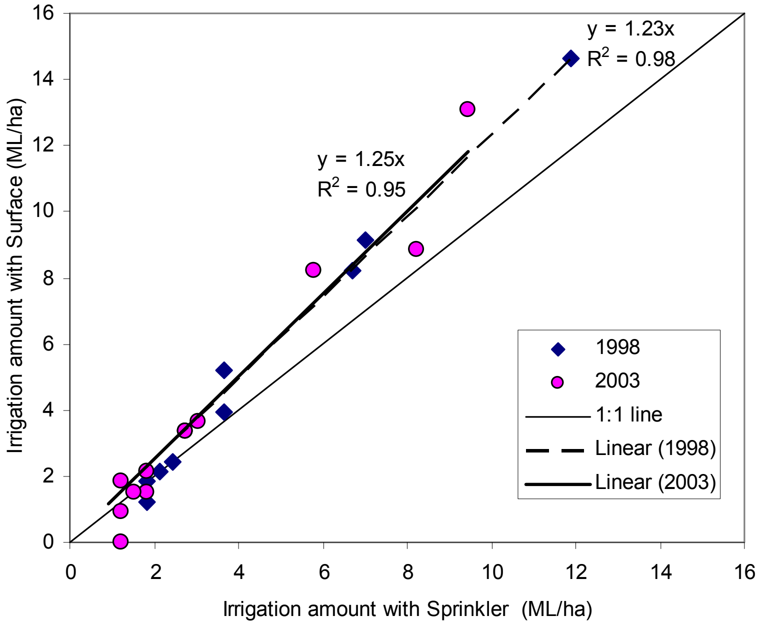


Figure 66 Relationships of cotton irrigation amounts applied with sprinkler and surface irrigation systems in the United States. Adapted from data reported in United States Department of Agriculture (1999 and 2004).

The average IWUI values were higher with sprinkler compared to surface irrigation for both the 1998 and 2003 data. The average IWUI values for both irrigation systems were higher in 2003 compared to 1998. The increase in IWUI from 1998 to 2003 was due to a combination of higher yields and lower irrigation applications.

WUE from farmer’s fields in Texas, USA

A dataset from farmer’s fields in Texas, USA, was obtained from the AgriPartners Crop Irrigation and Production Summary, 2005 program, which is available online (New, 2005). It includes data from several crops, including cotton. Data for cotton was available from 1998 to 2005. The cotton crop in Texas is irrigated mostly with centre pivots, but data include a few entries from fields using drip and furrow systems. The data available allowed calculation of the IWUI and the GPWUI (Table 33). Average yields in this dataset have tended to increase from 1998 to 2005, but are still very low compared to the yields obtained in Australia. Yields averaged 5.0 bales/ha, which is about half of the average yields from the crop competition data in Australia. Despite the low yields, both the IWUI and GPWUI values are much higher than the industry average reported by (Tennakoon and Milroy, 2003) for Australia, although they are still lower than the values from the Australian crop competition data.

Given the low yields obtained in Texas, the relatively high IWUI and GPWUI values are due to low irrigation, which averaged only 2.6 ML/ha. The low irrigation could be due to low irrigation requirements, but could also be due to the widespread use of high-efficiency irrigation systems such as centre pivots and drip systems. Also, it could be due to widespread use of deficit irrigation due to irrigation water shortages. In northern Texas, irrigation water mainly comes from the Ogallala formation of the High Plains Aquifer. This aquifer supplies water for the states of Texas, New Mexico, Oklahoma, Kansas, Colorado, Nebraska, Wyoming, and South Dakota. The water levels in this aquifer have been declining due to over-pumping combined with a multi-year drought, which has created water shortages in many of the states, and especially in Texas, where the declines in water levels have been more severe.

Because of the water shortages, which has probably forced farmers to deficit-irrigate, and because of the use of high efficiency irrigation systems, yields tend to increase linearly with either irrigation (Figure 67) or total water (R+I+S) (Figure 68). This pattern suggests that water is not being wasted. This is a different pattern than that obtained with the crop competition data in Australia (Figure 57), which tended to increase until the potential yield was reached, and then reached a plateau as additional water was applied, suggesting potential water savings by improving irrigation water management. These results indicate that while in Texas the IWUI is mainly being limited by low yields, in Australia improving irrigation water management could significantly increase IWUI since high yields are already being obtained. IWUI tended to decrease with irrigation amounts, following the same pattern obtained with the crop competition data from Australia. Again, this decreasing IWUI pattern with irrigation is expected in areas with a positive dryland yield. Figure 67 shows that on average, the dryland yield in the area was positive, as indicated by the intercept of the line (3.0 bales/ha).

Table 33. Cotton water use indices obtained by farmers in Texas, USA. Adapted from data reported by New (2005). Most data were from centre pivots, but also include a few entries from drip and surface systems.

Year	Number of Entries	Irrigation (mm)	R+I+S (mm)	PET (mm)	%PET	Yield (bales/ha)	IWUI (bales/ML)	GPWUI (bales/ML)
1998	9	280	483	555	87	4.47	1.70	0.92
1999	4	240	635	553	115	4.22	2.16	0.66
2000	6	293	572	643	92	4.01	1.41	0.72
2001	13	244	493	587	86	4.04	2.26	0.83
2002	15	313	647	758	87	5.21	1.86	0.80
2003	16	294	624	723	87	5.23	2.04	0.86
2004	9	254	647	719	91	4.82	1.98	0.74
2005	17	197	568	717	80	6.24	3.55	1.09
Total	**89**	**263.43**	**583.11**	**677.54**	**87.46**	**5.00**	**2.24**	**0.86**

R= rain, I=irrigation, S = soil water depletion, PET = potential evapotranspiration, %PET = 100(R+I+S)/PET, IWUE = irrigation water use index (lint yield/irrigation, GPWUI = gross production water use index (lint yield/total water [R+I+S]).

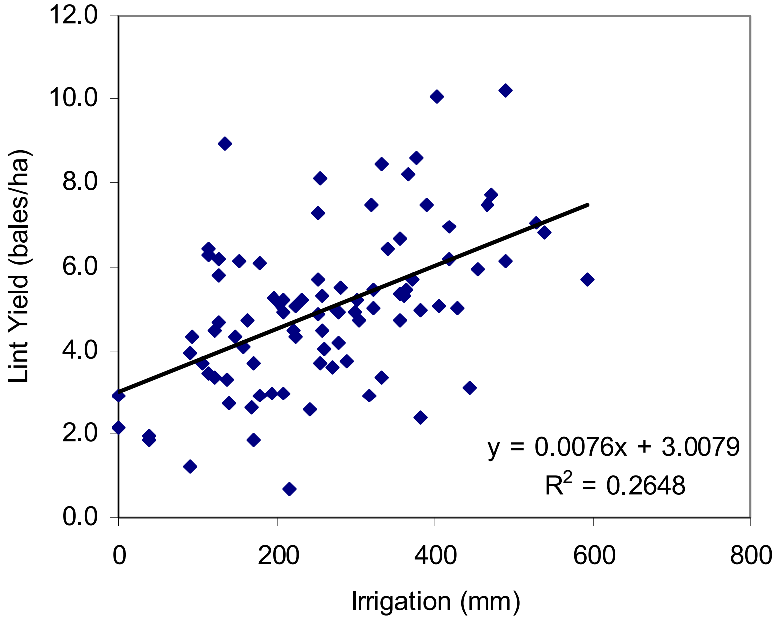


Figure 67 Cotton lint yield as a function of irrigation in Texas during 1998 to 2005. Adapted from data reported by New (2005)

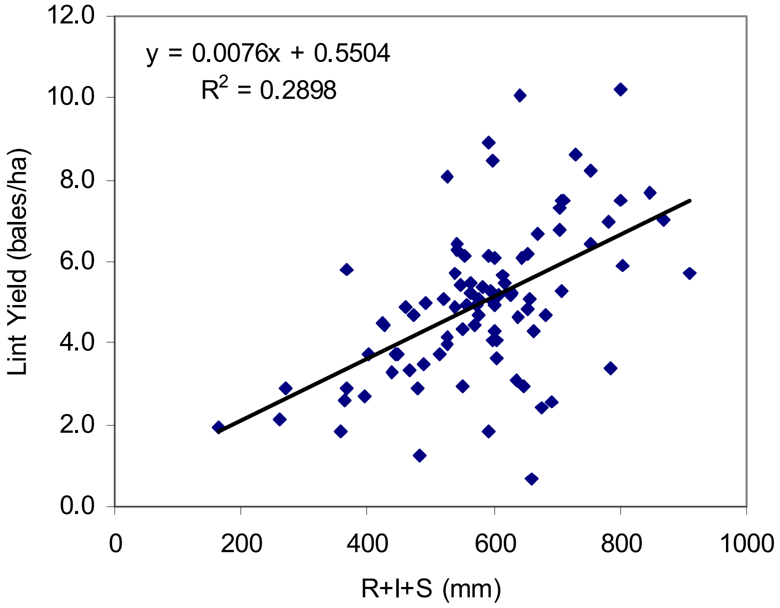


Figure 68 Cotton lint yield as a function of rain + irrigation+ soil water depletion (R+I+S) (total water) in Texas during 1998 to 2005. Adapted from data reported by New (2005)

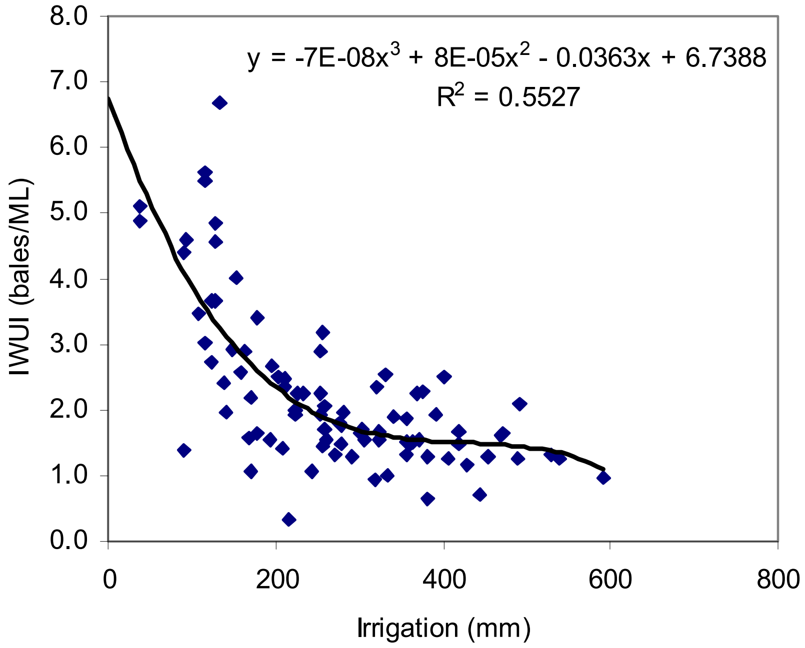


Figure 69 Cotton irrigation water use index (IWUI) as a function of irrigation in Texas during 1998 to 2005. Adapted from data reported by New (2005)

WUE from long-term experiments in Texas, USA

Data from long-term irrigation studies with cotton conducted at the USDA-ARS research station at Lubbock, Texas, USA, have been reported by Wanjura et al. (2002). The study was conducted during 1988 to 1999 using drip irrigation and included dryland, deficit-irrigated, and fully-irrigated treatments. The water balance data reported allowed calculation of the IWUI and GPWUI (Table 34). As with the farmer's data from Texas, the yields reported in this study were low compared to Australian yields, averaging 4.71 bales/ha. However, this average included dryland, deficit-irrigated, and fully-irrigated treatments, which produced an average relative yield of 79% compared to the fully-irrigated treatment. Still, the maximum yield during the study was only 7.18 bales/ha. A plot of yields for all treatment-years shows that yields increased with total water up to a point, after which it starting decreasing as total water became excessive (Figure 70). These results show that during some years, the fully-irrigated treatment was actually over-irrigated, which would lower the IWUI and GPWUI for this treatment. The average rain during the study was 150 mm, ranging from 38 to 249 mm. This rain was enough to produce a small, but positive dryland yield in all years in which a dryland treatment was included. Because of the positive dryland yield, the IWUI and GPWUI decreased with irrigation and total water, respectively (Figures 71 and 72).

The average IWUI and GPWUI obtained in this study were higher than the Australian cotton industry averages reported by Tennakoon and Milroy (2003). This is not surprising since data correspond to drip irrigation in Texas and surface irrigation in Australia. However, values in Texas were lower than the values obtained from the crop competition data in the Darling Downs, Australia. Despite using surface irrigation, the higher IWUI and GPWUI values in the Darling Downs are probably due to lower irrigation requirements (due to more rain) and much higher cotton yields, compared with Texas.

Table 34 Results from cotton irrigation studies in Lubbock, Texas. Adapted from data reported in Table 2 of Wanjura et al. (2002). Data include dryland, deficit-irrigated, and fully-irrigated treatments.

Year	Irrigation (mm)	Rain (mm)	Total water (mm)	Lint yield (kg/ha)	Lint yield (bales/ha)	Relative yield (%)	IWUI	GPWUI	IWUI	GPWUI
							--(kg/ha/mm)--		---(bales/ML)---	
1988	444.0	160.0	604.0	1431	6.30	100	3.22	2.37	1.42	1.04
	218.0	161.0	379.0	1073	4.73	75	4.92	2.83	2.17	1.25
	166.0	160.0	326.0	902	3.97	63	5.43	2.77	2.39	1.22
	926.0	155.0	1081.0	1147	5.05	80	1.24	1.06	0.55	0.47
	0.0	161.0	161.0	353	1.56	25		2.19		0.97
1989	594.0	180.0	774.0	595	2.62	71	1.00	0.77	0.44	0.34
	449.0	180.0	629.0	839	3.70	100	1.87	1.33	0.82	0.59
	372.0	180.0	552.0	673	2.96	80	1.81	1.22	0.80	0.54
	631.0	189.0	820.0	554	2.44	66	0.88	0.68	0.39	0.30
	0.0	180.0	180.0	630	2.78	75		3.50		1.54
1990	1117.0	195.0	1312.0	931	4.10	63	0.83	0.71	0.37	0.31
	539.0	195.0	734.0	1401	6.17	95	2.60	1.91	1.15	0.84
	328.0	195.0	523.0	1389	6.12	94	4.23	2.66	1.87	1.17
	658.0	195.0	853.0	1485	6.54	100	2.26	1.74	0.99	0.77
	0.0	195.0	195.0	706	3.11	47		3.62		1.59
	346.0	195.0	541.0	1165	5.13	78	3.37	2.15	1.48	0.95
	436.0	195.0	631.0	1345	5.93	91	3.08	2.13	1.36	0.94
1991	409.0	249.0	658.0	1006	4.43	100	2.46	1.53	1.08	0.67
	470.0	249.0	719.0	947	4.17	94	2.01	1.32	0.89	0.58
	455.0	249.0	704.0	845	3.72	84	1.86	1.20	0.82	0.53
	365.0	249.0	614.0	879	3.87	87	2.41	1.43	1.06	0.63
	305.0	249.0	554.0	637	2.81	63	2.09	1.15	0.92	0.51
	288.0	249.0	537.0	757	3.33	75	2.63	1.41	1.16	0.62
	0.0	249.0	249.0	481	2.12	48		1.93		0.85
1992	351.0	109.0	460.0	1335	5.88	100	3.80	2.90	1.68	1.28
	120.0	109.0	229.0	1248	5.50	93	10.40	5.45	4.58	2.40
	360.0	108.0	468.0	1263	5.56	95	3.51	2.70	1.55	1.19
	334.0	109.0	443.0	1263	5.56	95	3.78	2.85	1.67	1.26
	284.0	109.0	393.0	1270	5.59	95	4.47	3.23	1.97	1.42
	326.0	109.0	435.0	1146	5.05	86	3.52	2.63	1.55	1.16
	183.0	109.0	292.0	1231	5.42	92	6.73	4.22	2.96	1.86
	0.0	109.0	109.0	1060	4.67	79		9.72		4.28
1993	454.0	171.0	625.0	1447	6.37	93	3.19	2.32	1.40	1.02
	442.0	171.0	613.0	1467	6.46	95	3.32	2.39	1.46	1.05
	304.0	171.0	475.0	1548	6.82	100	5.09	3.26	2.24	1.44
	0.0	171.0	171.0	668	2.94	43		3.91		1.72
	159.0	171.0	330.0	1267	5.58	82	7.97	3.84	3.51	1.69
1994	524.0	92.0	616.0	1481	6.52	91	2.83	2.40	1.25	1.06
	505.0	92.0	597.0	1460	6.43	90	2.89	2.45	1.27	1.08
	387.0	92.0	479.0	1630	7.18	100	4.21	3.40	1.86	1.50
	0.0	92.0	92.0	609	2.68	37		6.62		2.92
1995	439.0	86.0	525.0	1572	6.93	98	3.58	2.99	1.58	1.32
	594.0	83.0	677.0	1522	6.70	95	2.56	2.25	1.13	0.99
	395.0	84.0	479.0	1608	7.08	100	4.07	3.36	1.79	1.48
	380.0	84.0	464.0	1388	6.11	86	3.65	2.99	1.61	1.32
	380.0	84.0	464.0	1424	6.27	89	3.75	3.07	1.65	1.35
	358.0	84.0	442.0	927	4.08	58	2.59	2.10	1.14	0.92
1996	336.0	80.0	416.0	1198	5.28	100	3.57	2.88	1.57	1.27
	336.0	80.0	416.0	1169	5.15	98	3.48	2.81	1.53	1.24
	273.0	47.0	320.0	847	3.73	71	3.10	2.65	1.37	1.17
	273.0	47.0	320.0	864	3.81	72	3.16	2.70	1.39	1.19
1997	0.0	229.0	229.0	365	1.61	24		1.59		0.70
	53.0	229.0	282.0	855	3.77	57	16.13	3.03	7.11	1.34
	213.0	229.0	442.0	1251	5.51	83	5.87	2.83	2.59	1.25
	320.0	229.0	549.0	1510	6.65	100	4.72	2.75	2.08	1.21
1998	0.0	148.0	148.0	262	1.15	18		1.77		0.78
	440.0	148.0	588.0	1440	6.34	100	3.27	2.45	1.44	1.08
1999	0.0	38.0	38.0	78	0.34	7		2.05		0.90
	418.0	38.0	456.0	1204	5.30	100	2.88	2.64	1.27	1.16
Maximum	1117.0	249.0	1312.0	1630	7.18	100	16.13	9.72	7.11	4.28
Minimum	0.0	38.0	38.0	78	0.34	7	0.83	0.68	0.37	0.30
Average	**330**	**152**	**482**	**1069**	**4.71**	**79**	**3.72**	**2.62**	**1.64**	**1.16**

Total water = rain + irrigation,

IWUI = irrigation water use index (lint yield/irrigation)

GPWUI = gross production water use index (lint yield/total water)

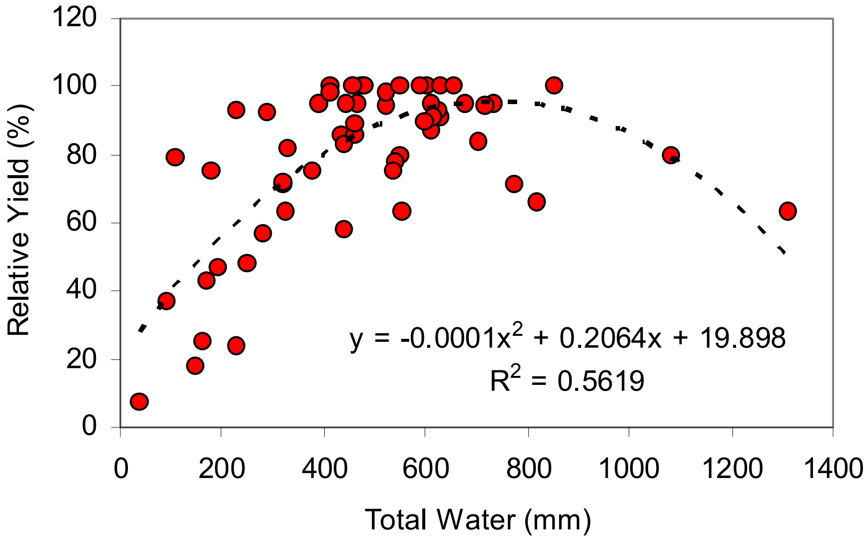


Figure 70 Cotton relative yield as a function of total water (rain + irrigation), obtained in research studies from 1988-1999 in Lubbock, Texas. Adapted from data reported in Table 2 of Wanjura et al. (2002).

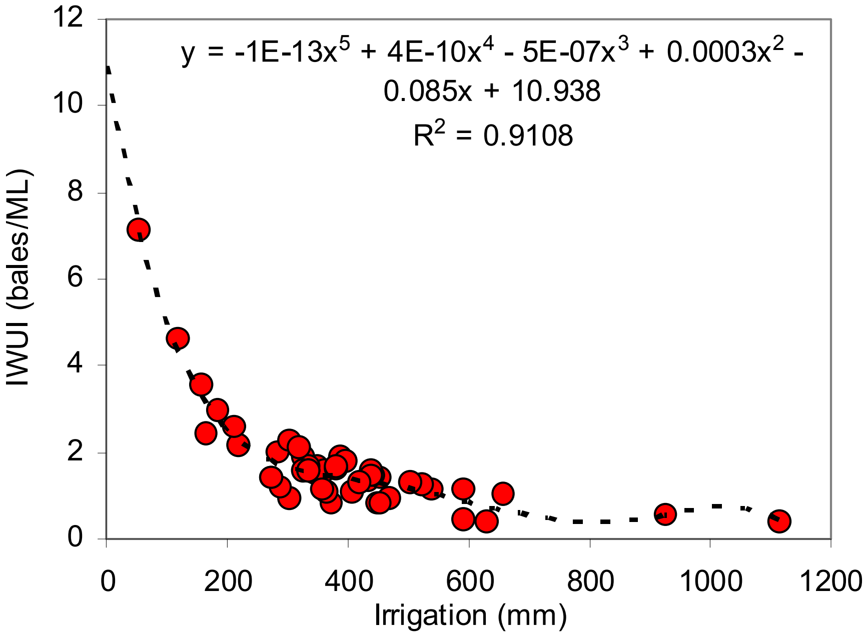


Figure 71 Cotton irrigation water use index (IWUI= lint yield/irrigation) as a function of irrigation, obtained in research studies from 1988-1999 in Lubbock, Texas. Adapted from data reported in Table 2 of Wanjura et al. (2002).

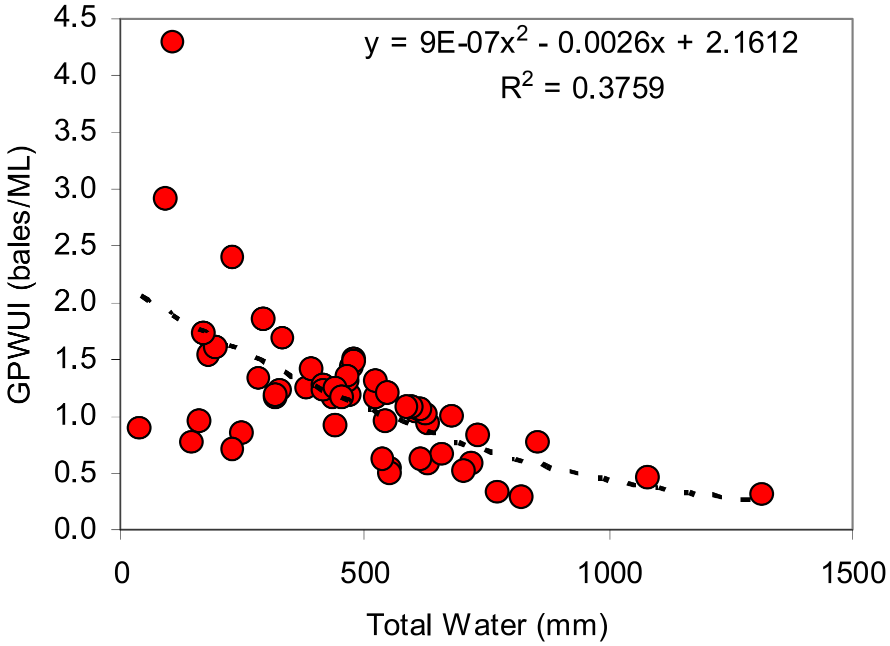


Figure 72 Cotton gross production water use index (GPWUI= lint yield/total water) as a function of total water (rain + irrigation) obtained in research studies from 1988-1999 in Lubbock, Texas. Adapted from data reported in Table 2 of Wanjura et al. (2002).

WUE from research plots in Uzbekistan

Results of a study comparing management options for furrow irrigation systems in Uzbekistan were reported by Horst et al. (2007). Management options included irrigating every furrow or alternate furrows using either continuous or surge flow. The water balance data collected allowed calculating the CWUI, IWUI, and GPWUI (Table 35). In this study, all four treatments were fully-irrigated. Irrigating alternate furrow with surge flow reduced irrigation from 881 mm to 492 mm, a water savings of 389 mm or 44%, compared with irrigating every furrow with continuous flow, while obtaining only slightly lower yields.

Unlike the data from Texas, yields in this study were very high, averaging 13.69 bales/ha. This yields were even higher than the average of the crop competition data in the Darling Downs (9.34 bales/ha). The CWUI, IWUI, and GPWUI were very high, averaging 2.56, 2.11, and 1.90 bales/ML of ET, irrigation and total water, respectively. Irrigating alternate furrows instead of every furrow, and using surge flow instead of continuous flow, tended to increase all of the indices. The CWUI, IWUI, and GPWUI values reported in this study were much higher than the Australian cotton industry averages reported by Tennakoon and Milroy (2003). The values in this study are from research plots while the Australian values are from actual commercial farms. Despite the much higher yields, however, the average IWUI obtained in this study (2.11 bales/ML) is lower than the average obtained from the crop competitions data in the Darling Downs (2.75 bales/ML). This is due to the much lower irrigation requirements in the Darling Downs compared to Uzbekistan. In this study, irrigation averaged 6.72 ML/ha, while in the Darling Downs, irrigation averaged only 3.5 ML/ha. Because of the higher yields, however, the GPWUI was still higher in Uzbekistan, compared to the Darling Downs competition data.

Table 35 Effect of surface irrigation management options on cotton water use indices in Uzbekistan. Adapted from data reported by Horst et al. (2007)

Irrigation Treatment		Irrigation	Total Water	ET	Yield	Yield	CWUI	IWUI	GPWUI	CWUI	IWUI	GPWUI
Furrow	**Flow**	|--------------	(mm)	------------|	(bales/ha)	(kg/ha)	|------------	(bales/ML)	---------------|	|------------	(kg/ha/mm)	------------|
Every Furrow	Continous Flow	881	951	598	14.94	3391	2.50	1.70	1.57	5.67	3.85	3.57
Every Furrow	Surge Flow	693	763	598	13.40	3041	2.24	1.93	1.76	5.09	4.39	3.99
Alternate Furrow	Continous Flow	623	693	480	13.16	2988	2.74	2.11	1.90	6.23	4.80	4.31
Alternate Furrow	Surge Flow	492	562	480	13.26	3010	2.76	2.69	2.36	6.27	6.12	5.36
Average		**672**	**742**	**539**	**13.69**	**3108**	***2.56***	***2.11***	***1.90***	**5.81**	**4.79**	**4.30**

CWUI = crop water use index (yield/ET), IWUI =irrigation water use index (yield/irrigation), GPWUI= gross production water use index (yield/total water)

Total water = rain + irrigation, ET = evapotranspiration, yield refer to lint yield

WUE for Upland and Pima Cotton in Arizona and California

Grismer (2002) compiled CWUI data from Upland and Pima cotton from different regions in Arizona and California. The yields reported in this study were low compared to irrigated yields obtained in Australia. Estimates of cotton ET, net irrigation requirements (NIR), lint yields, CWUI, and irrigation water value (IWV) (US$ per unit NIR), including their coefficient of variation, for the different regions are shown in Table 31. He found that cotton lint yields in interior valley regions of California were weakly correlated with ET while in desert regions of Arizona and California yields were not correlated with ET. The low correlation between yield and ET in this study is not surprising since ET data were not actually measured and data for different regions were pooled together. Average Upland cotton yields were higher in Arizona (6.36 bales/ha) compared to California (5.85 bales/ha). The opposite was observed for Pima cotton, which averaged 4.64 bales/ha in Arizona and 5.51 bales/ha in California. In both states, Upland cotton yielded more than Pima cotton.

Average ET and NIR were much higher in Arizona than in California. This explains the higher values of CWUI obtained in California compared with Arizona. The CWUI in Arizona averaged only 0.58 and 0.42 bales/ML of ET for Upland and Pima Cotton, respectively. CWUI values were higher in California, averaging 0.74 and 0.72 bales/ML of ET, respectively. These averages are much lower than the average CWUI of 1.08 bales/ML of ET for the Australian cotton industry reported by Tennakoon and Milroy (2003). The low CWUI values in this study, especially in Arizona, resulted from a combination of low yields and high ET. Although ET in this study varied little among regions, with a coefficient of variation (CV) of less than 5%, the CWUI values were very variable among regions, with CV values ranging from 11.24 to 16.64%, reflecting the variability in cotton yields within and among regions. Despite the low CWUI values obtained in this study, by reviewing published studies Grismer (2002) concluded that CWUI values of 0.88-1.32 bales/ML of ET (2-3 kg/ha/mm) were possible in California and Arizona, which are much lower than the CWUI values obtained in Uzbekistan (2.56 bales/ML of ET) (Horst et al., 2007). Since net irrigation requirements were less in California compared with Arizona, the irrigation water value (IWV) (US$ per unit NIR) was higher in California. The IWV was higher when used to irrigate Pima Cotton than Upland cotton in both states.

Table 36. Estimates of cotton ETc, IWR, WUE, and IWV and their variability for Upland and Pima cotton in Arizona and California, USA. Adapted from data in Table 5 of Grismer (2002).

State	Location	ETc (mm)	ETc CV(%)	NIR (mm)	NIR CV (%)	Yield (kg/ha)	Yield (bales/ha)	CWUI (kg/ha/mm)	CWUI (bales/ML)	CWUI CV (%)	IWV (US$/ha/m)	IWV CV (%)
Arizona	Lapaz	1362	3.6	1304	4.6	1757	7.74	1.29	0.57	10.2	$1,870	8.6
(Upland Cotton)	Maricopa	1023	3.1	920	7.8	1361	5.99	1.33	0.59	6.7	$2,111	12.5
	Mohave	1034	5.0	999	6.2	1313	5.78	1.27	0.56	17.8	$1,867	16.5
	Pinal	1007	4.8	887	10.2	1349	5.94	1.34	0.59	8.4	$2,180	16.3
	Yuma	1035	5.3	987	5.7	1428	6.29	1.38	0.61	13.1	$2,057	15.6
	Average	**1092**	**4.4**	**1019**	**6.9**	**1444**	**6.36**	**1.32**	***0.58***	**11.2**	**$2,017**	**13.9**
						0						
Arizona	Lapaz	1362	3.6	1304	4.6	1253	5.52	0.92	0.41	18.2	$2,094	20.4
(Pima Cotton)	Maricopa	1023	3.1	920	7.8	921	4.06	0.90	0.40	9.8	$2,244	17.4
	Pinal	1007	4.8	887	10.2	906	3.99	0.90	0.40	13.2	$2,266	23.3
	Yuma	1035	5.3	987	5.7	1128	4.97	1.09	0.48	21.5	$2,507	27.8
	Average	**1107**	**4.2**	**1025**	**7.1**	**1054**	**4.64**	**0.95**	***0.42***	**15.7**	**$2,278**	**22.2**
California	C. Sac V.	656	6.8	565	16.1	1135	5.00	1.73	0.76	28.5	$3,293	26.6
(Upland Cotton)	S. Sac. V.	672	6.1	405	27.9	1102	4.85	1.64	0.72	17.1	$4,821	49.7
	N. SJV	684	3.9	630	6.4	1436	6.33	2.10	0.93	10.3	$3,777	15.3
	C. SJV	750	3.2	697	6.7	1433	6.31	1.91	0.84	8.6	$3,411	10.9
	S. SJV	776	3.7	704	11.1	1296	5.71	1.67	0.74	12.0	$3,038	6.0
	S. desert	990	2.3	853	14.2	1327	5.84	1.34	0.59	19.6	$2,334	24.3
	Low desert	1008	3.6	958	5.9	1381	6.08	1.37	0.60	20.4	$2,384	35.3
	Average	**791**	**4.2**	**687**	**12.6**	**1329**	**5.85**	**1.68**	***0.74***	**16.6**	**$3,294**	**24.0**
California	C. SJV	750	3.2	697	6.7	1328	5.85	1.77	0.78	10.0	$4,172	13.6
(Pima Cotton)	SJV	776	3.7	704	11.1	1172	5.16	1.51	0.67	16.6	$3,500	9.6
	Average	**763**	**3.5**	**701**	**8.9**	**1251**	**5.51**	**1.64**	***0.72***	**13.3**	**$3,836**	**11.6**

ETc = crop evapotranspiration, CV = coefficient of variation (=S.D./mean), NIR =irrigation water requirement (= ET-rain)
CWUI = crop water use index (= lint yield/Etc), IWV = irrigation water value (= US$ per unit NIR)

International Comparisons of cotton yields

The latest statistics on cotton yields reported by the USDA for 2003/04 (United States Department of Agriculture, 2005) by countries and by regions around the world are shown in Figures 73 and 74, respectively. They show that Australia leads the world in cotton yield with an average of 8.3 bales/ha, which is almost three times the reported world average of 2.8 bales/ha. These average yields, however, are lower than the yield potential for each country since they include both irrigated and dryland production. It also should be kept in mind that the yield rankings presented here only correspond to the 2003/04 season and could change from season to season. This dataset did not report water information and therefore the water use indices could not be calculated.

International Comparisons of cotton IWUI

Data on yield and water used in different countries have been presented in the Water Footprint of Nations (Chapagain and Hoekstra, 2004), which can be used to obtain an estimate of the average IWUI for the main cotton producing countries. Cotton yields, irrigation water use, and IWUI, according to this source, for the different countries are shown in Figures 73 to 74. They show that on average for 1997 to 2001, the highest cotton yields were obtained in Israel, followed by Australia, with high variability among countries. These yield data differ from the latest statistics from the USDA presented previously, which rank Australia with the highest yield. Difference between the two datasets could be due to the fact that they represent different periods (1997-2001 vs 2003/04).

Irrigation water used varied widely from 4.4 ML/ha in China to 8.8 ML/ha in Iraq. The large range in irrigation water use is due to differences in crop water requirements (largely a function of differences in weather conditions among countries) and irrigation water management. The IWUI was highest for China and Israel, followed by Australia. However, as previously discussed, the IWUI is not a good index for comparison. Comparisons using the CWUI, which is more meaningful for comparison than the IWUI are presented in the following section.

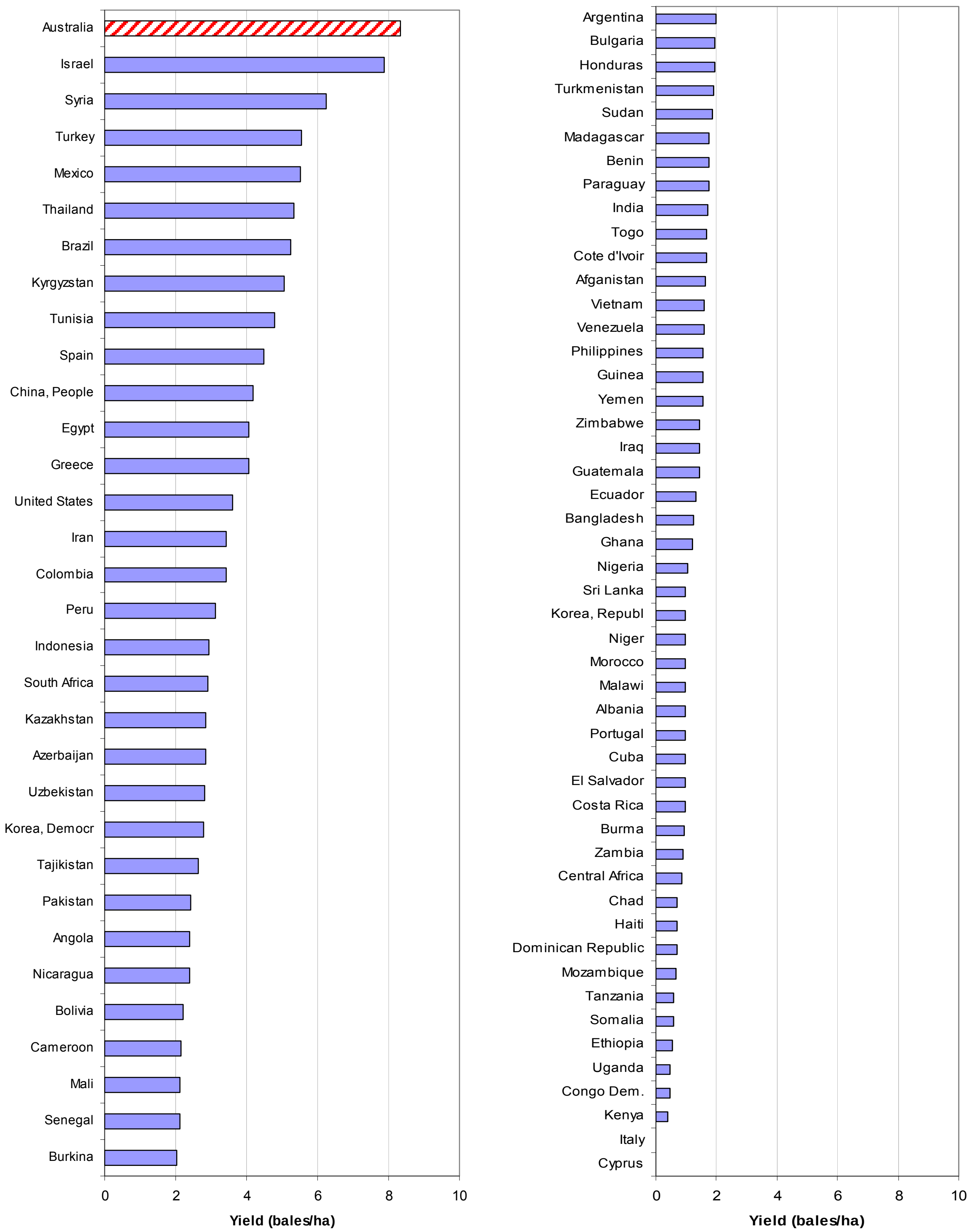


Figure 73 Cotton yields by country for 2003/04. Adapted from data reported in United States Department of Agriculture (2005).

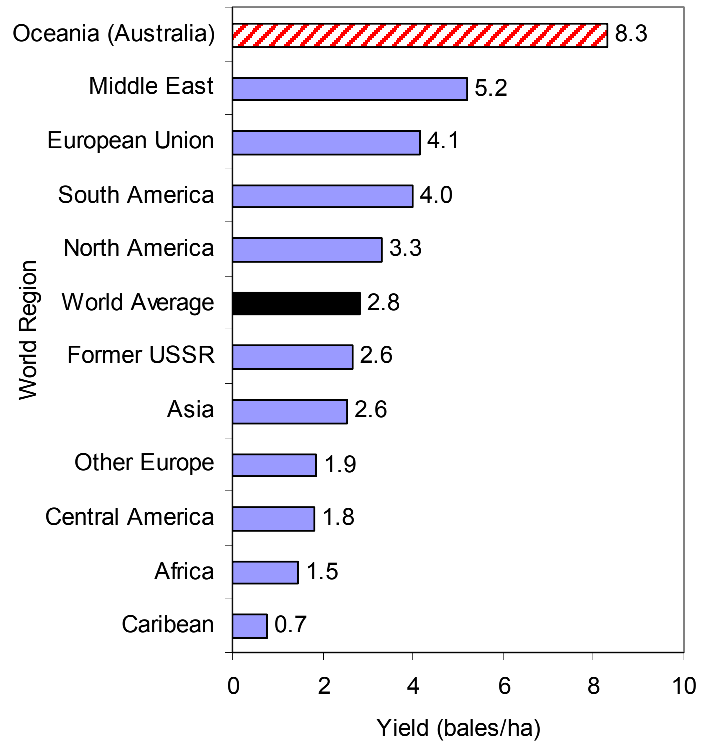


Figure 74 Cotton yields by world region for 2003/04. Adapted from data reported in United States Department of Agriculture (2005).

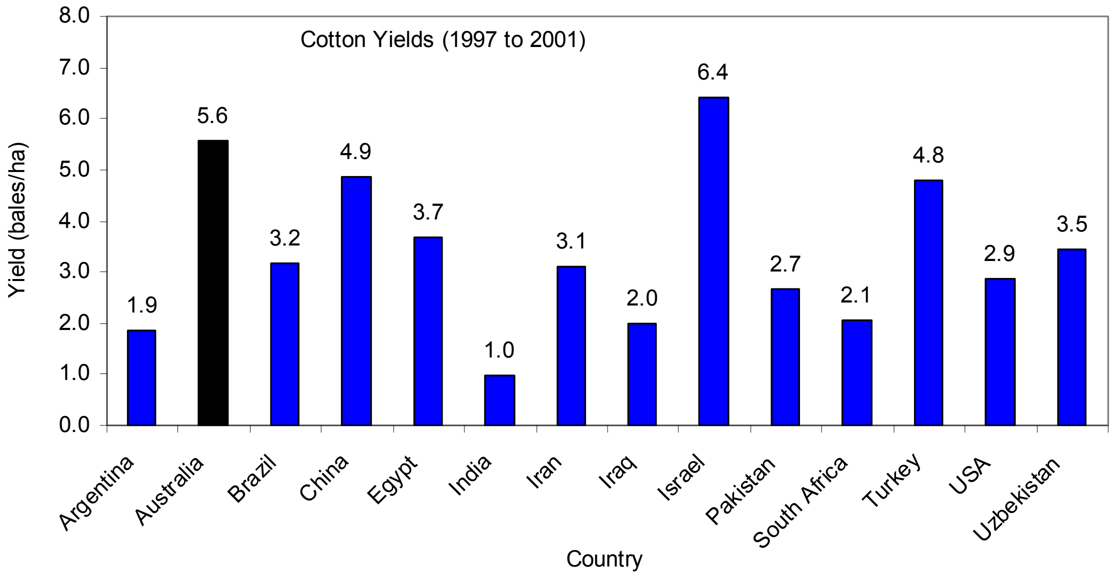


Figure 75 Cotton yields by country. Adapted from data in Chapagain and Hoekstra (2004).

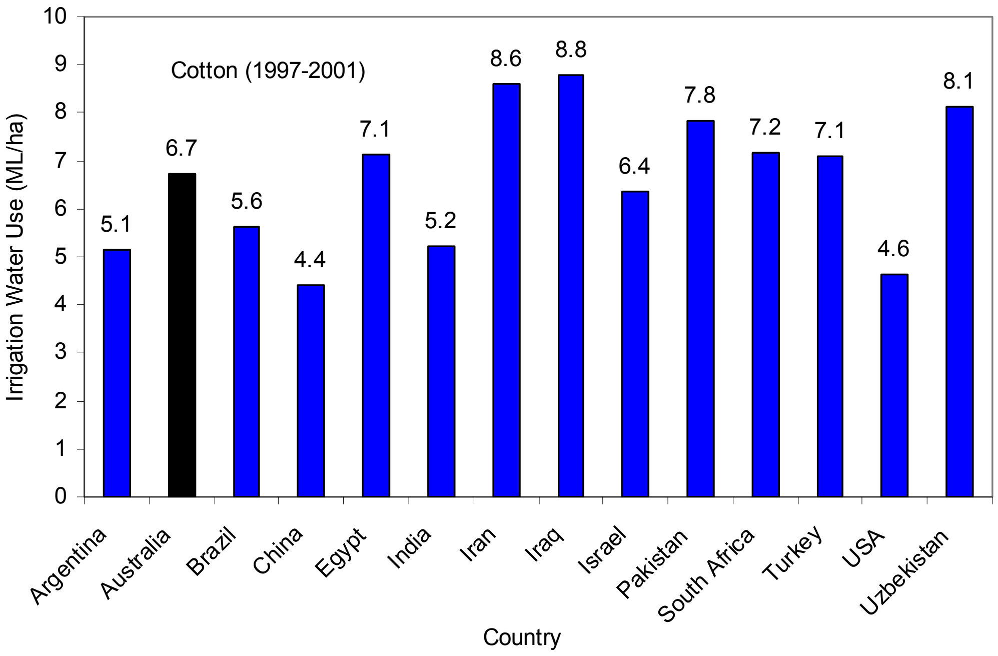


Figure 76 Cotton irrigation water use by country. Adapted from data in Chapagain and Hoekstra (2004).

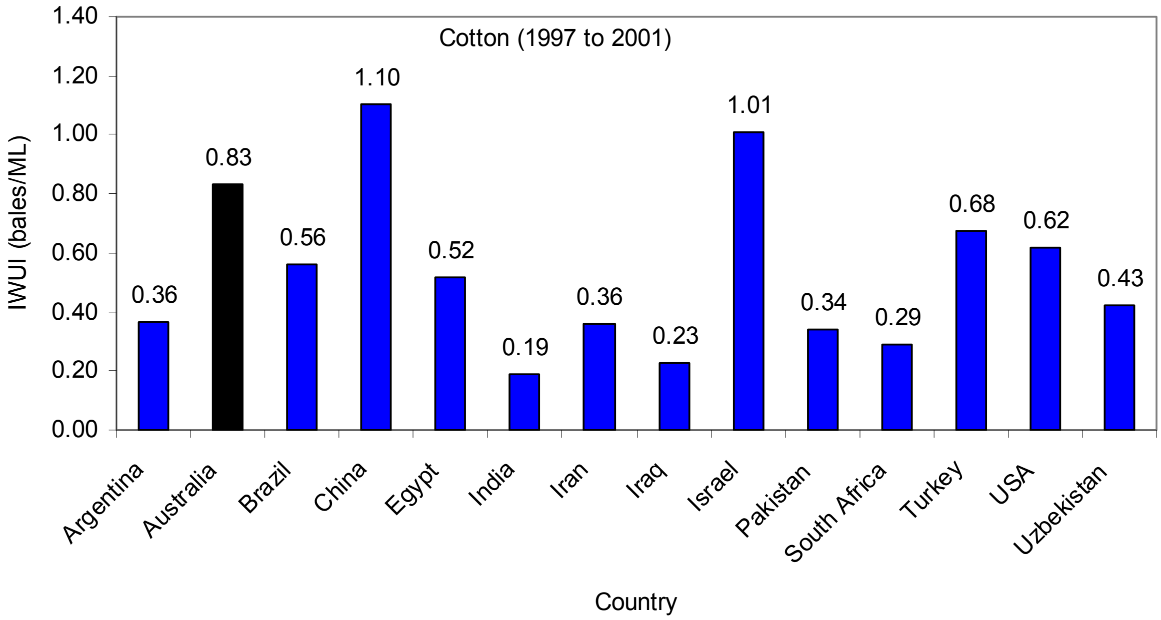


Figure 77 Cotton irrigation water use index (IWUI =lint yield/irrigation) by country. Adapted from data in Chapagain and Hoekstra (2004)

International Comparisons of cotton CWUI

International comparisons of cotton crop water use index (CWUI) have been conducted by several authors. For instance, Zwart and Bastiaanssen (2004) presented median CWUI values for cotton lint and seed from several locations around the world, which are summarized in Figures 78 and 79. Median CWUI values for lint ranged from 0.62 bales/ML of ET in Texas, USA, to 4.67 bales/ML in Uzbekistan, with an overall average of 1.51 bales/ML of ET. The CWUI value for Uzbekistan seems extremely high and are almost twice as high as the values recently obtained in Uzbekistan by Horst et al. (2007). The CWUI for Australia was higher than for most locations in the USA, including Texas, Arizona, and California (except for one location in Five Points, California). However, the CWUI for Australia was lower than those obtained at one location in California (Five Points), Israel, China, Turkey, and Uzbekistan.

The CWUI for seed, varied from 1.89 kg/ha/mm in Turkey to 3.70 kg/ha/mm in Argentina with an average of 2.58 kg/ha/mm. No CWUI for seed was reported for Australia. As expected, due to variations in yield potentials and net irrigation requirements among locations, the CWUI values varied considerably and it is therefore difficult to make comparisons among location and to get a good sense about irrigation performance based on the CWUI alone.

A similar review of international data on cotton crop water use index (CWUI) was conducted by Grismer (2002). He reviewed published CWUI values from the USA (from California, Arizona, and Texas), and from other countries including Argentina, Turkey, China, and Israel, taking information from published sources (Anac et al., 1999; Ayars et al., 1999; Ayars and Soppe, 2001; Baumhardt and Lascano, 2000; Davis, 1983; Grimes, 1982; Hunsaker et al., 1998; Jin et al., 1999; Preito and Angueira, 1999; Saranga et al., 1998; Soppe, 2000; Styles and Bernasconi, 1994; Wanjura et al., 1996). CWUI values are summarized in Table 32, which are highly variable due to variations in net irrigation requirements, yield potentials and crop management among locations and growing seasons.

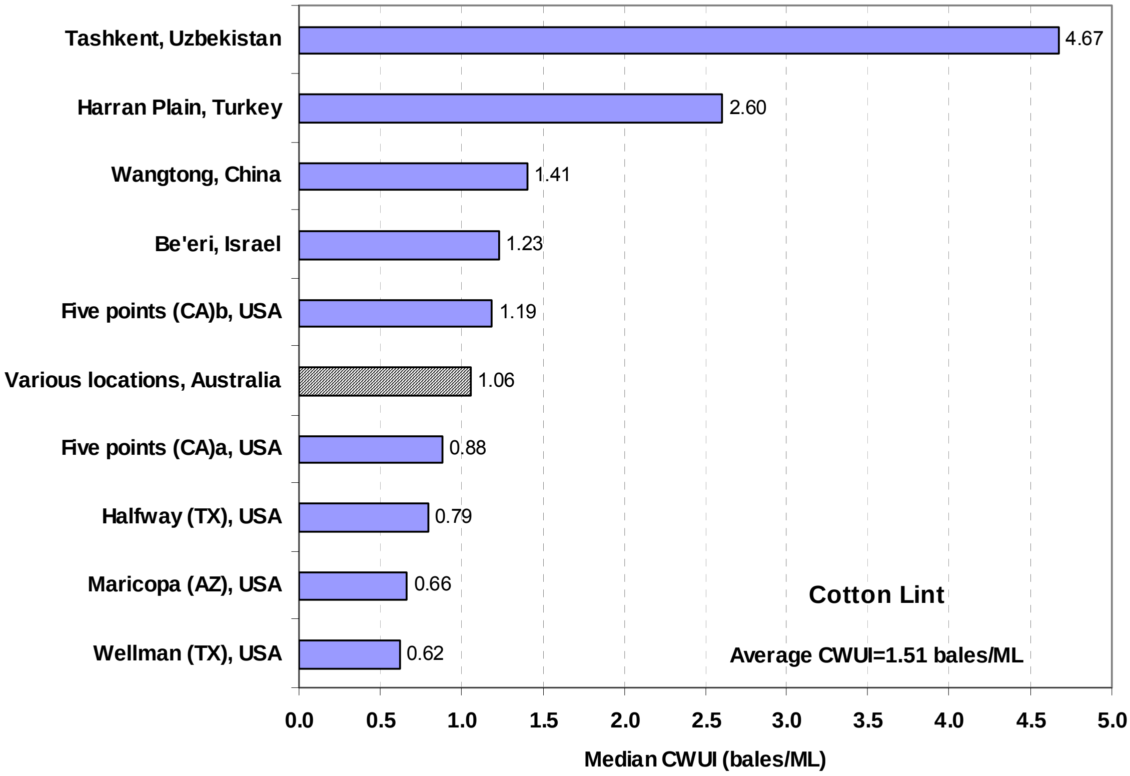


Figure78 Median values of published cotton crop water use index (CWUI= lint yield/evapotranspiration) for different locations around the world. Adapted from data reported in appendix A of Zwart and Bastiaanssen (2004). The CWUI value for Australia is highlighted and was obtained from data reported by Tennakoon and Milroy (2003).

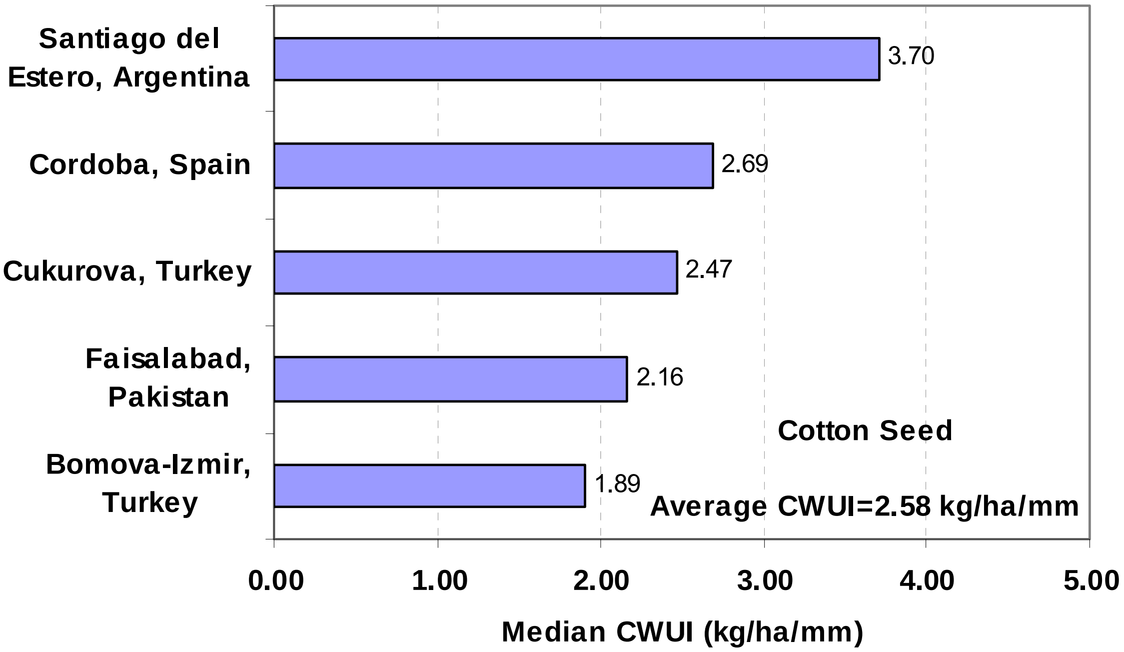


Figure 79 Median values of published cotton crop water use index (CWUI= seed yield/evapotranspiration) for different locations around the world. Adapted from data reported in appendix A of Zwart and Bastiaanssen (2004). No data for Australia were given.

Table 37 Summary of recent cotton lint yields, ETc, and crop water use index (CWUI) obtained at several locations around the world. Adapted from data reported in Table 1 of Grismer (2002)

Location	Irrigation Method	Comments	Year	ETc (mm)	Lint Yield (Mg/ha)	Lint Yield (bales/ha)	CWUI (kg/ha/mm)	CWUI (bales/ML)	Reference
USA (California)	Drip	Parlier lysimeter	1998	710	1.32	5.81	1.86	0.82	Soppe (2000);
	Drip		1999	845	2.16	9.52	2.56	1.13	and Ayars and Soppe (2001)
	Sprinkler/Furrow	Westlake farms	1997	567	1.16	5.11	2.04	0.90	
			1998	561	0.62	2.73	1.12	0.49	
			1999	561	1.23	5.42	2.19	0.96	
	Drip	Field study	1992	549	1.78	7.84	3.24	1.43	Ayars et al. (1999)
			1993	691	2.04	8.99	2.95	1.30	
	Furrow	Field study	1992	437	1.40	6.17	3.20	1.41	
			1993	645	1.50	6.61	2.33	1.03	
	Drip and furrow	Field study		713-805	1.23-1.55	5.42-6.83	1.53-2.03	0.67-0.89	Styles and Bernasconi (1994)
	Drip	Early irrigation	1993-1994	620	1.46	6.43	2.36	1.04	Wanjura et al. (1996)
		Delayed-Low frequency	1993-1994	477	1.59	7.00	3.33	1.47	
		Delayed-High frequency	1993-1994	605	1.46	6.43	2.42	1.07	
	Subsurface drip			700	1.45	6.39	2.07	0.91	Davis (1983)
	Drip			760	1.57	6.92	2.07	0.91	Grimes (1982)
USA (Arizona)	Level basin	Low frequency	1993-1994	620	1.46	6.43	2.36	1.04	Hunsaker et al. (1998)
		Low-high-low-frequency	1993-1995	477	1.59	7.00	3.33	1.47	
		High frequency	1993-1996	605	1.46	6.43	2.42	1.07	
USA (Texas)	Dryland	Clean Tillage	1992-1995	200-300	0.29-0.51	1.28-2.25	1.51-1.66	0.67-0.73	Baumhardt and Lascano (2000)
		Wheat residue	1992-1996	300	0.37	1.63	1.22	0.54	
Argentina	Furrow		1991	736	1.68	7.40	2.29	1.01	Preito and Angueira (1999)
			1992	495	1.92	8.46	3.87	1.70	
			1993	631	1.95	8.59	3.09	1.36	
Turkey	Furrow		1993	834	1.16	5.11	1.39	0.61	Anac et al. (1999)
			1994	899	1.21	5.33	1.34	0.59	
China	Furrow	No mulch	1994	506	0.85	3.74	1.67	0.74	Jin et al. (1999)
(East Hebei Plain)		Plastic mulch	1994	426	1.13	4.98	2.62	1.15	
Israel (Negev)	Drip	Full Irrigation	1994-1995	491-566			2.1-3.4	0.93-1.50	Saranga et al. (1998)
		Irrigation at 50-100% ETo	1994-1995	349-390			2.1-3.5	0.93-1.54	

ETc =crop evapotranspiration, CWUI =crop water use index (lint yield/ETc)

A review of international data on cotton crop water use index (CWUI) was also given by Hearn (1994), which included CWUI values obtained in several locations in the USA (California, New Mexico, Arizona, and Texas), Israel, Spain, and Australia (Hodgson et al., 1990; Howell et al., 1984; Mateos et al., 1991; Meiri et al., 1992; Orgaz et al., 1992; Radin, 1992; Sammis, 1981). Figure 77 compares CWUI values obtained in different countries and different regions of the USA. Reported CWUI values varied from 0.67 bales/ML of ET in New Mexico, USA, to 1.66 bales/ML of ET obtained in Israel, averaging 1.18 bales/ML of ET. A comparison of CWUI obtained under drip and furrow irrigation in Arizona (USA), Spain, and Australia is shown in Figure 80. Higher CWUI values were obtained with drip compared to furrow irrigation in Spain and Arizona, and the opposite was observed in the Australian study.

As noted earlier, in the Australian study more water was applied with the drip system than with the furrow system, which explains the lower CWUI values observed with drip. Hearn (1994) also presented data from Texas showing how CWUI can be affected by row spacing. Figure 82 shows that CWUI increased as cotton row spacing decreased from 1 m to 0.33 m.

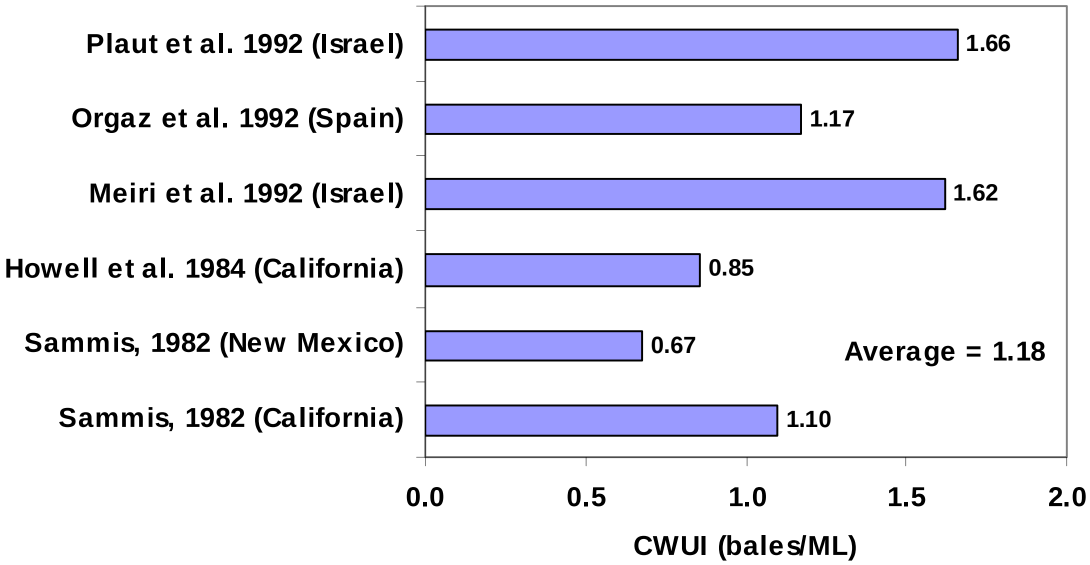


Figure 80 Cotton crop water use index (CWUI=Lint yield/Evapotranspiration) for different locations around the world. Adapted from values reported in Table 3 of Hearn (1994).

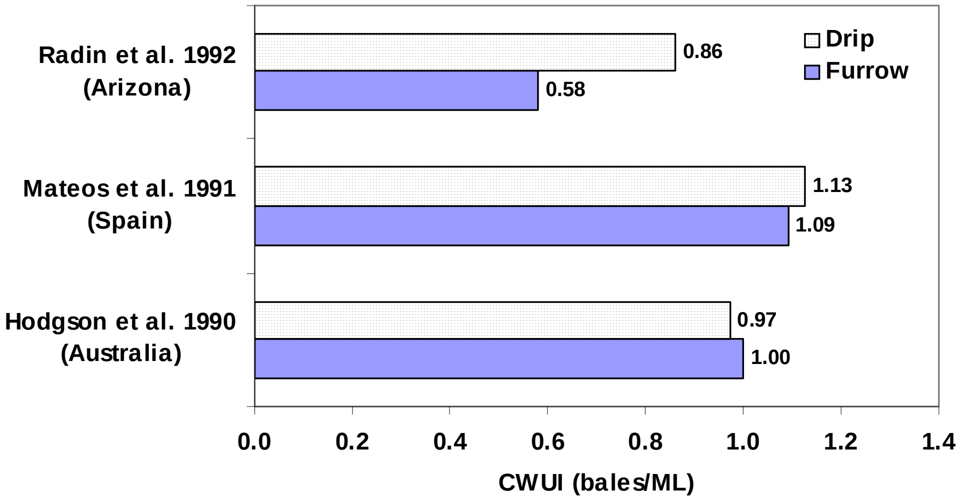


Figure 81 Cotton crop water use index (CWUI=Lint yield/Evapotranspiration) reported for drip and furrow irrigation systems. Adapted from values reported in Table 4 of Hearn (1994).

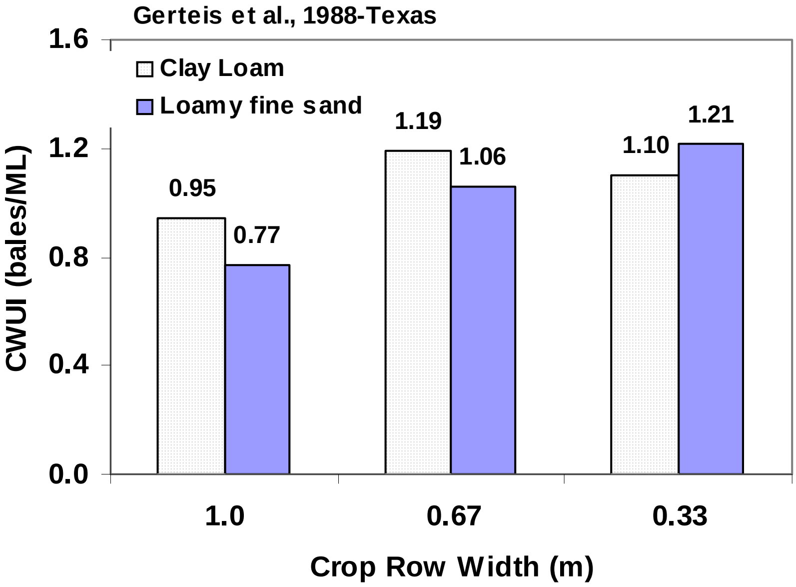


Figure 82 Cotton crop water use index (CWUI=Lint yield/Evapotranspiration) obtained in Texas for three crop row widths. Adapted from values reported in Table 4 of Hearn (1994).

Irrigation efficiencies in the Australian cotton industry

Several studies have evaluated irrigation performance in the Australian cotton industry. For instance, Goyne et al. (2000) reported cotton irrigation efficiencies estimated for the Darling Downs, McIntyre valley and Emerald over two seasons, which averaged only 56% (Table 38).

Table 38. Estimated irrigation efficiencies (%) for cotton in three regions of Australia. Adapted from results of desktop study reported in Table 3 of Goyne et al. (2000).

Region	No. farms	1997/98	1998/99	Average
Darling Downs	3	40	62	51
McIntyre	1	67	60	64
Emerald	5	50	59	55
Average		**52**	**60**	**56**

Dalton et al. (2001) evaluated irrigation performance in the Australian cotton industry and found that the whole-farm irrigation efficiencies (WFIE) (water utilized by crop/water delivered to farm) ranged between 21 and 65%. They also found that on-farm storage efficiency ranged from 50 to 85%, in-field application efficiency ranged from 70 to 88%, and in-field deep drainage losses ranged from 11 to 30% over the season. Most cotton farmers in Australia previously believed that water losses by deep drainage were insignificant in the heavy clay soils in which most of the cotton is grown. They also found that waterlogging created by furrow irrigation in the heavy clay soils was a potential source of significant yield reduction. They even suggested that cotton yields could be increased by 20% by reducing waterlogging. The partitioning of the estimated water losses within the farm and the whole-farm irrigation efficiency from this study were summarised by Hood and Wigginton (2005)(Table 39). The study estimated whole-farm irrigation efficiency of only 43%, which was even lower than the values previously reported by Goyne et al. (2000). Surprisingly, the main water losses were due to evaporation and seepage during storage, which combined for 35% of the on-farm water losses, followed by field seepage (10%).

Table 39. Water losses on Australian cotton farms obtained by Dalton et al. (2001), as summarized by Hood and Wigginton (2005). The losses were calculated as a % of the water available at the farm gate.

Source	Loss (%)
Dam Evaporation	30
Dam Seepage	5
Distribution Evaporation	4
Distribution Seepage	6
Field Evaporation	2
Field Seepage	10
Total Losses	**57**
Irrigation Efficiency	**43**

Dalton et al. (2001) concluded that realistic potential improvements in water management in cotton were to:

- Reduce evaporation from storages by 20-50%
- Reduce deep drainage by 10-15%
- Increase cotton yields by 20% by reducing waterlogging

Tennakoon and Milroy (2003) also reported whole-farm irrigation efficiency values for each of the cotton producing areas for three seasons (Fig. 80). Values varied considerably with season and valley. The efficiencies were higher than the average reported by Dalton et al. (2001), but still the industry average whole-farm irrigation efficiency only ranged from 54 to 60%.

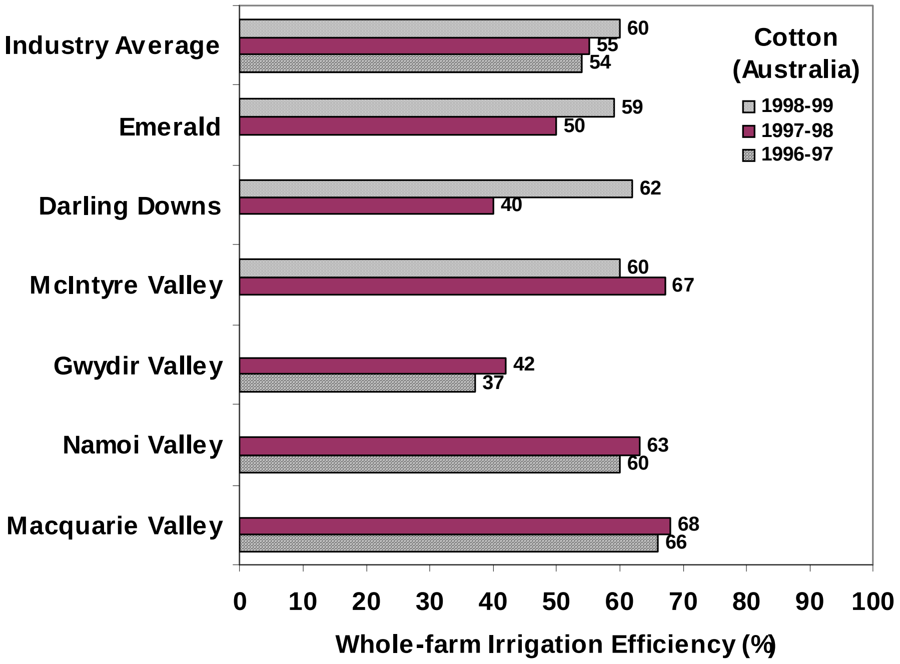


Figure 83 Whole-farm irrigation efficiencies obtained during three seasons in the different cotton producing valleys in Queensland and New South Wales, Australia. Adapted from average values reported in Table 5 of Tennakoon and Milroy (2003).

More recently, Smith et al. (2005) reported results of evaluation of surface irrigation events in cotton fields in Queensland. They found that at the field level:

- Irrigation application efficiencies varied widely from 17-100% with an average of 48%,
- Deep percolation losses averaged 42.5 mm per irrigation, representing an annual loss of up to 2.5 ML/ha.
- Irrigation application efficiencies in the range of 85-95% were achievable by optimising furrow irrigation in all but the most adverse conditions.

Also, reviewing available data on deep drainage in irrigated cotton in Australia, Silburn and Montgomery (2004) found that for furrow–irrigated fields, annual deep drainage rates of 1-2 ML/ha were typical, and that values ranging from 0.03 to 9 ML/ha had been observed.

In summary, the above studies suggest that about half of the water reaching the Australian cotton farms is lost during storage, conveyance, and field application, with only half available for crop water use. Most water losses seem to occur during storage and conveyance, before the water reaches the field. Land & Water Australia (2005) reported average conveyance losses in irrigation water supply schemes in Australia at 28%, which was relatively low compared to other countries (Figure 84). In some areas, attempts to reduce these losses through canal lining are being undertaken (Figure 85). Since runoff from furrow irrigation is mostly captured and reused, water losses in the field are mostly due to deep drainage (seepage), with small losses due to evaporation from the soil surface. There seems to be potential for significantly reducing field deep drainage by optimising furrow irrigation or changing to more efficient irrigation systems.

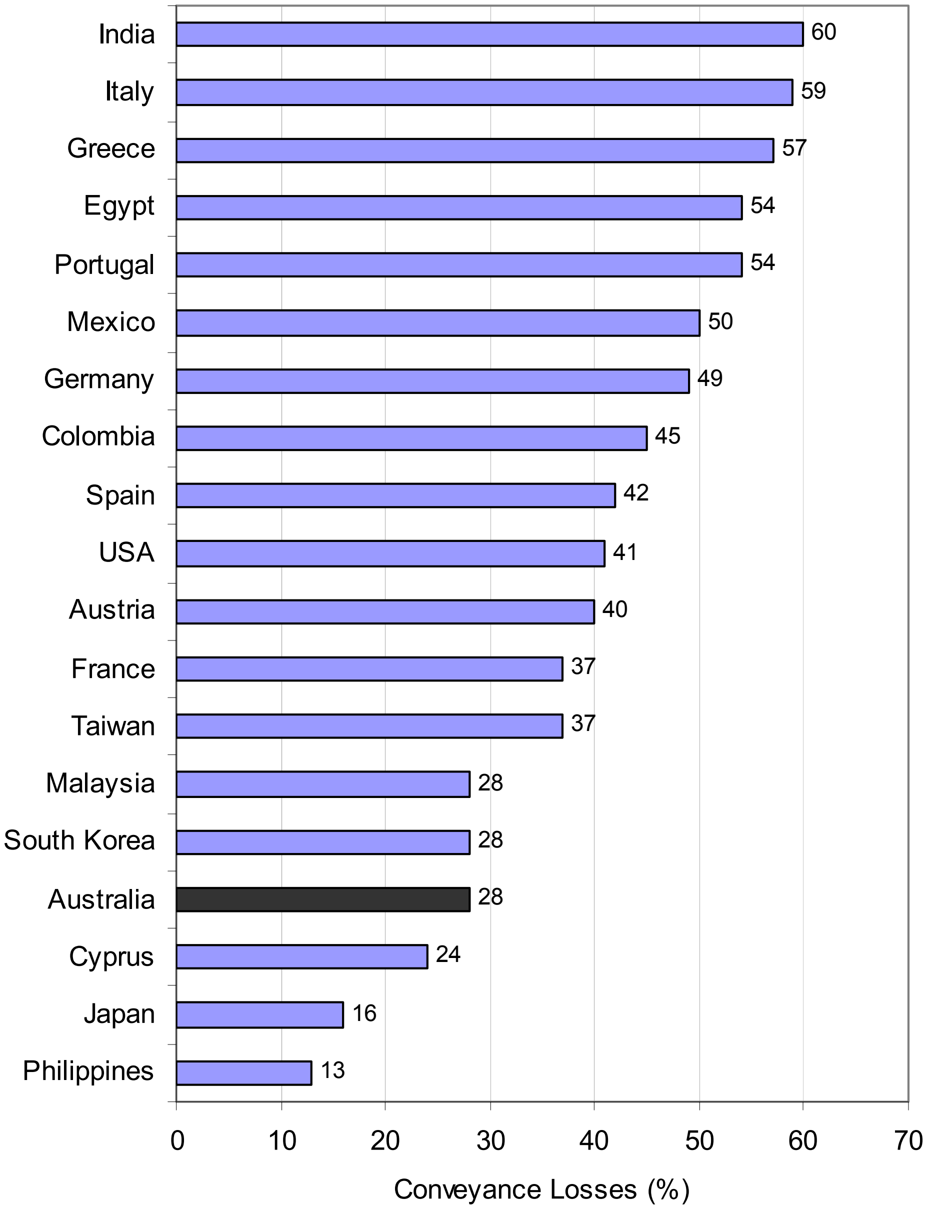


Figure 84 Conveyance losses in irrigation water supply schemes in various countries. Adapted from data in Land & Water Australia (2005).

Figure 85 Lined irrigation canal near Emerald, Australia (Photo by Jose Payero).

This situation, however, is not unique to the cotton industry. In a recent speech by the Australian Prime Minister, when announcing "A National Plan for Water Security" (Howard, 2007), provided the following figures for irrigation in Australia:

- Irrigated agriculture uses 14,000 GL/year, which is about 70% of all water use in Australia.
- Between 10-30% of water diverted from rivers is lost before reaching the farm gate.
- Up to 20% of water delivered to the farm gate may be lost in distribution channels on-farm.
- Around 60% of water used for irrigation is applied using high volume, ineffective gravity irrigation methods.
- More than 10-15% of water applied to crops is lost through over watering, whereas scheduling tools and observational data could more precisely match water application to crop water requirements.
- Inaccurate measurement of water diversions from rivers and water use on farms is leading to unintentional and intentional over use.

There are also opportunities for improving irrigation scheduling. Montagu et al. (2006) when evaluating the adoption of objective irrigation scheduling tools in Australia stated that:

"…Whereas the increase in adoption rate is heartening, it is sobering to realise that almost four out of five farmers who derive their living from using water do not measure how much water is in their soil. Moreover, the most recent statistics show that only 9% of growers plan future investment in soil water monitoring equipment."

However, they also stated that cotton was among the only three industries in Australia in which a scientific method of scheduling irrigation was adopted by 10% or more of irrigators. The methods include the use of tensiometers in the fruit/nut industry, tensiometers and soil probes in the grape industry, and soil probes in the cotton industry.

Improving WUE

WUE can be improved by modifying either or both of its components ("yield" and "water"). In the past, considerable improvements in WUE have come from increasing crop yield by improving both crop varieties and agronomic practices. There is still much potential to focus on the "water" part of the WUE equation. However, since CWUI increases with irrigation (as ET increases), and IWUI decreases with irrigation in areas with positive dryland yields, like in most agricultural areas, defining which of these indices the industry wants to increase is the first step towards defining the strategy to follow. Different and often opposite strategies need to be used to increase the CWUI, IWUI or economic returns.

How to increase CWUI

- Increasing crop yields by developing varieties with higher yield potential, and improving agronomic practices.
- Increasing crop yield by minimising crop water stress and increasing transpiration by:
  - If water is not limited, fully-irrigating to meet crop water requirements
  - If water is limited and deficit irrigation is required:
    - If possible, timing irrigations to minimise stress during high ET periods.
    - Reducing irrigated area to better meet crop water requirements instead of deficit-irrigating a larger area.
- Increasing yields by controlling yield limiting factors like insects, weeds, diseases, crop nutrition, soil salinity, waterlogging, etc
- Reducing evaporation water losses, which can be achieved by:
  - Avoiding irrigating more frequently than necessary to meet crop water needs.
  - When possible, avoiding irrigation during the early stage of the crop when crop cover is low and evaporation is high compared to transpiration. This strategy, however, needs to be used with caution, since delaying irrigation can create crop stress and significantly reduce yields.
  - Using mulching by crop residue or other feasible means.
  - Minimizing unnecessary tillage that exposes stored soil water to evaporation.
  - Using irrigation systems and management strategies that minimise evaporation (such as subsurface drip irrigation, and irrigating alternate furrows instead of every furrow when using furrow irrigation).
  - Using the highest plant density that best management agronomic practices and water availability allow.

How to increase IWUI

- Increasing yield using the strategies listed above that do not require additional irrigation.
- At the field level, decreasing irrigation by:
  - Deficit-irrigating a larger area instead of fully-irrigating a smaller area.
  - Increasing irrigation efficiency
    - Using more efficient irrigation systems (drip, sprinkler, optimised furrow)
    - Decreasing irrigation requirements by capturing more rain and reducing evaporation (reduced tillage, residue management, land levelling, terracing, crop rotation, proper sowing time…)

- Improving irrigation scheduling and management
    - Applying the right amount of irrigation at the right time.
    - Optimising the irrigation system to improve irrigation uniformity and reduce water losses (gated pipes, surge flow, alternate furrows…).
    - Recycling water
- At the whole-farm level, decreasing water losses during storage and distribution.

How to increase economic returns

Unlike the IWUI, the increasing trend in CWUI with ET does not depend on the sign of the dryland yield. Therefore, for areas and seasons with a positive dryland yield, the CWUI will tend to increase with irrigation while the IWUI will tend to decrease. Since the two indices have opposite behaviour with irrigation, the question then is which of the two indices the industry should try and increase. The answer to this question will probably be the strategy that maximizes profits without wasting water.

A recent study from India, Kar et al. (2007) showed that increases in ET due to irrigation also increased CWUI and profitability per unit area for three crops (linseed, safflower, and mustard)(Fig. 83). Similar increasing returns per unit area ($/ha) with increasing crop water use for wheat, barley, and canola in Australia was reported by Montagu et al. (2006). This means that profitability per unit area ($/ha) increased with CWUI and decreased with increasing IWUI. It should be kept in mind that the CWUI can be maximised by over-irrigating. Over-irrigation will waste water and will not produce additional yield, in fact, it can reduce yields. Therefore, if the objective is to maximise CWUI, care should be taken to increase it without over-irrigating.

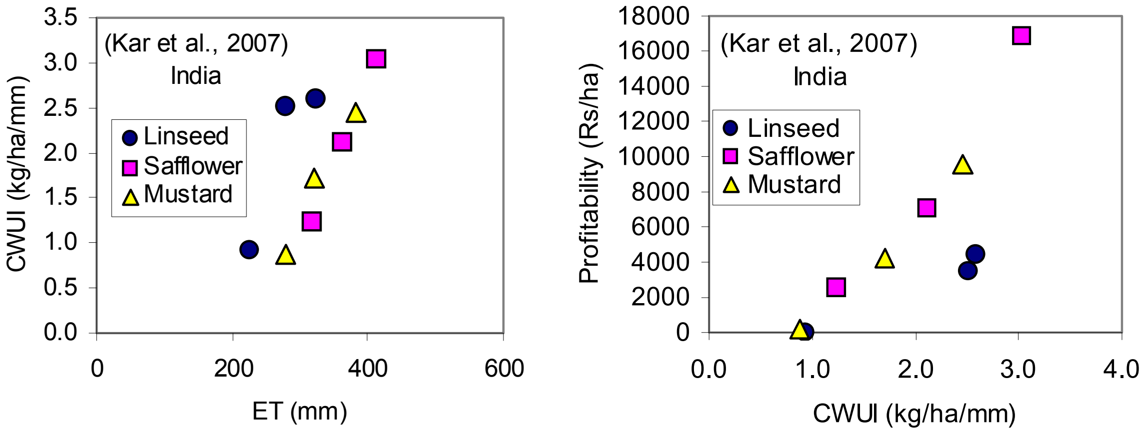


Figure 86 Relationships between evapotranspiration (ET), crop water use index (CWUI = yield/ET), and profitability of three crops in India. Adapted from data reported in Table 5 of Kar et al. (2007).

The study in India, however, only analysed the profitability per unit area ($/ha), which would be appropriate in situations where area is the factor limiting production. However, in other situations other factors like water, capital, labour, etc, can be limiting. In Australia, land is abundant and water is usually the limiting factor. In this situation, water saved by deficit-irrigation could be used to increase the area planted. Therefore, it is imperative to consider not the profit per unit area ($/ha), but the profit per unit of irrigation ($/ML), and even more importanlyt, to identify the water management or water allocation option that will maximize profits of the whole farming enterprise ($/farm). This type of economic analysis is usually conducted using optimization and/or simulation techniques (English et al., 2002; Gibb, 1995; Martin et al., 1989; Martin and Supalla, 2005; Norton et al., 2000).

A simpler analysis, however, considering the gross margin per unit area ($/ha), per unit irrigation ($/ML) and for the whole farm ($/farm) for cotton in Australia was conducted by Keefer (1989), who reported an economic analysis for deficit irrigation scenarios for cotton at Emerald in the 1980s. A similar economic analysis for wheat, barley, and canola, assuming land-limiting and water-limiting scenarios was conducted by Montagu et al. (2006). For the economic analysis for cotton, Keefer (1989) used a “yield versus irrigation” response function derived from deficit irrigation experiments at Emerald (Figure 87). In his analysis, he used a total water allocation of 850 ML, and limited the area to be irrigated to a maximum of 200 ha. He used a variable cost of production for 1989 of $900/ha and a water charge of $14.85/ML. He determined a whole-farm budget assuming cotton prices of $300/bale and $500/bale.

A similar analysis is reported below based on the analysis of Keefer (1989), using the cost of production of 1989, which is shown in Table 40. To be more realistic, however, the current analysis imposed no limit on area that could be irrigated if water was available, and used a water allocation of 3000 ML to be able to fully irrigate around 800 ha, which would be more typical of a cotton farmer in Australia (Newnham et al., 2006). Also, to eliminate experimental errors in the yield versus irrigation response function, which could interfere with the economic analysis, yield for each irrigation level was estimated using the equation derived in Figure 87 (yield=1.4377x + 2.4304).

The gross margins in Table 40 have been plotted in figs. 88 to 90, which show that for 1989 the gross margin per unit area ($/ha) decreased as area irrigated increased as a result of decreasing irrigation per unit area. A similar decreasing pattern resulted for the two cotton prices. On the other hand, the gross margin per unit irrigation ($/ML) either increased or decreased with area irrigated, depending on cotton prices. The gross margin per unit irrigation ($/ML) decreased with area irrigated for the lower cotton price ($300/bale) and increased with area irrigated for the higher cotton price ($500/bale). The gross margin for the whole farm ($/farm) followed a similar pattern as the gross margin per unit irrigation ($/ML), decreasing with area irrigated for the low cotton price and increasing with area irrigated for the higher cotton price. In this analysis there is a break-even cotton price (somewhere between $300 and $500/bale) at which the slopes of the lines in Figures 88 and 89 will change signs.

It should be kept in mind that the previous analysis used a fixed variable cost regardless of irrigation level, which is not always valid. Also, a fixed “yield versus irrigation” response function was assumed. However, this response function in fact changes with season and location, as reported by Gibb (1995). Also, using the water saved by deficit-irrigating to increase area irrigated is not a viable option in all situations. The previous analysis does not consider overhead costs (administration, labour, machinery, etc, that should be included to determine profits.

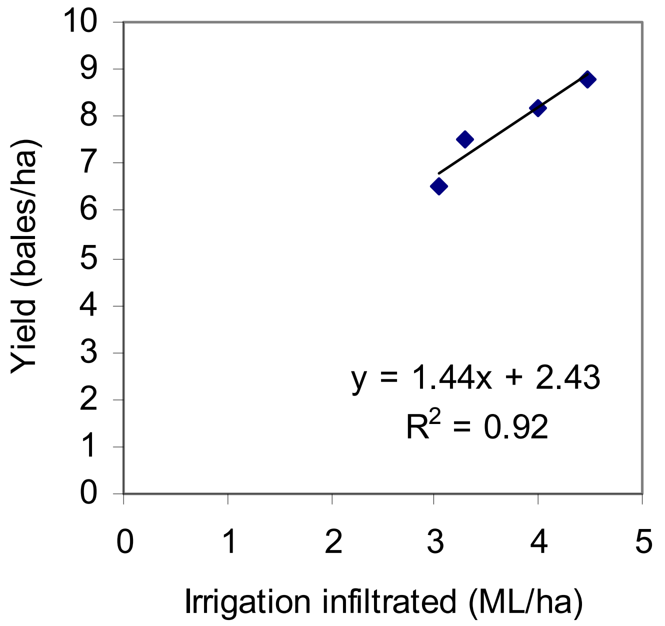


Figure 87 Cotton lint yield as a function of irrigation infiltrated used in economic analysis at Emerald by Keefer (1989).

Table 40. Economic analysis for cotton under different deficit-irrigation scenarios at Emerald, Australia. Based on the data reported by Keefer (1989), using cost of production from 1989.

Soil water deficit to apply irrigation (mm)	**75 mm**	**100 mm**	**120 mm**	**150 mm**
Water allocation (ML/farm)	3000	3000	3000	3000
Average number of irrigations	6	4	3	2.5
Irrigation Applied (ML/ha)	5.6	5	4.1	3.8
Irrigation efficiency (%)	80	80	80	80
Irrigation infiltrated (ML/ha)	4.5	4.0	3.3	3.0
Maximum crop area (ha)	536	600	732	789
Yield (bales/ha)	8.9	8.2	7.1	6.8
Relative yield (%)	100	92	81	77
Farm Budget:				
Whole farm production (bales/farm)	4752.5	4908.7	5228.8	5369.2
Variable cost ($/ha)	$900	$900	$900	$900
Water charge ($/ML)	$14.85	$14.85	$14.85	$14.85
Farm variable cost ($/farm)	$482,143	$540,000	$658,537	$710,526
Farm water charge ($/farm)	$44,550	$44,550	$44,550	$44,550
Farm variable costs + water charge	$526,693	$584,550	$703,087	$755,076
Crop price ($/bale)	**$300**	**$300**	**$300**	**$300**
Gross income ($/farm)	$1,425,744	$1,472,616	$1,568,646	$1,610,765
Gross margin for whole farm ($/farm)	$899,051	$888,066	$865,560	$855,689
Gross margin per unit area ($/ha)	$1,678	$1,480	$1,183	$1,084
Gross margin per unit irrigation ($/ML)	$300	$296	$289	$285
Crop price ($/bale)	**$500**	**$500**	**$500**	**$500**
Gross income ($/farm)	$2,376,240	$2,454,360	$2,614,411	$2,684,608
Gross margin for whole farm ($/farm)	$1,849,547	$1,869,810	$1,911,324	$1,929,532
Gross margin per unit area ($/ha)	$3,452	$3,116	$2,612	$2,444
Gross margin per unit irrigation ($/ML)	$617	$623	$637	$643

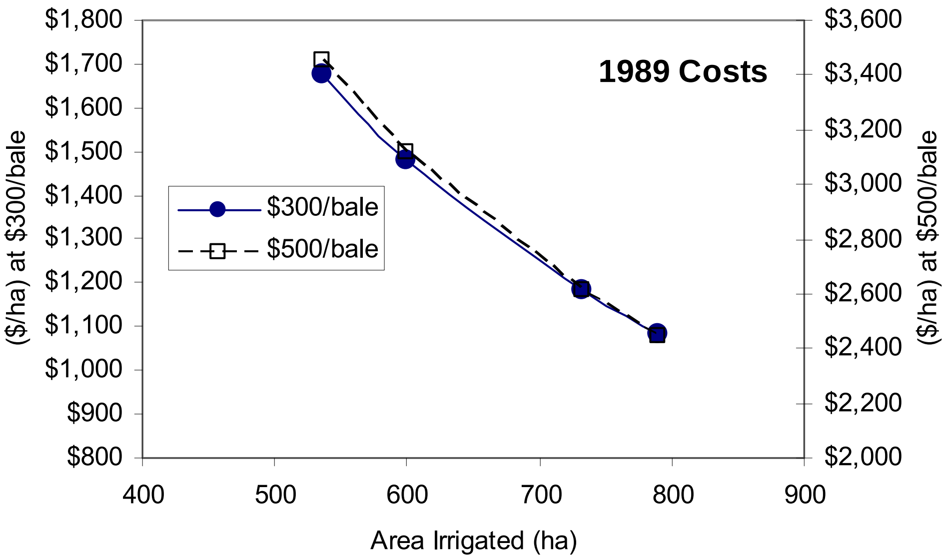


Figure 88 Gross margin per unit area ($/ha) as a function of area irrigated for an irrigation water allocation of 3000 ML and cotton prices of $300 and $500/bale. Based on 1989 production costs for Emerald, Australia (Keefer, 1989).

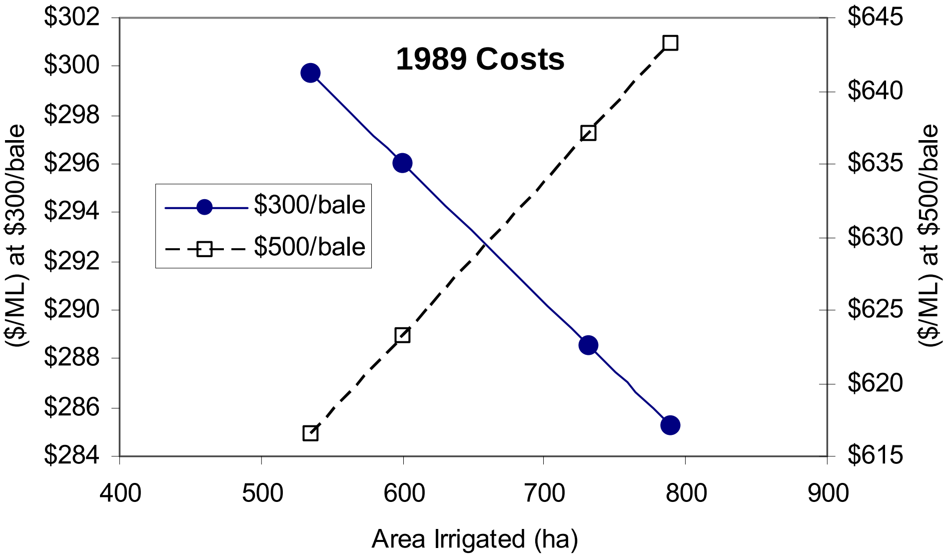


Figure 89 Gross margin per unit irrigation ($/ML) as a function of area irrigated for an irrigation water allocation of 3000 ML and cotton prices of $300 and $500/bale. Based on 1989 production costs for Emerald, Australia (Keefer, 1989).

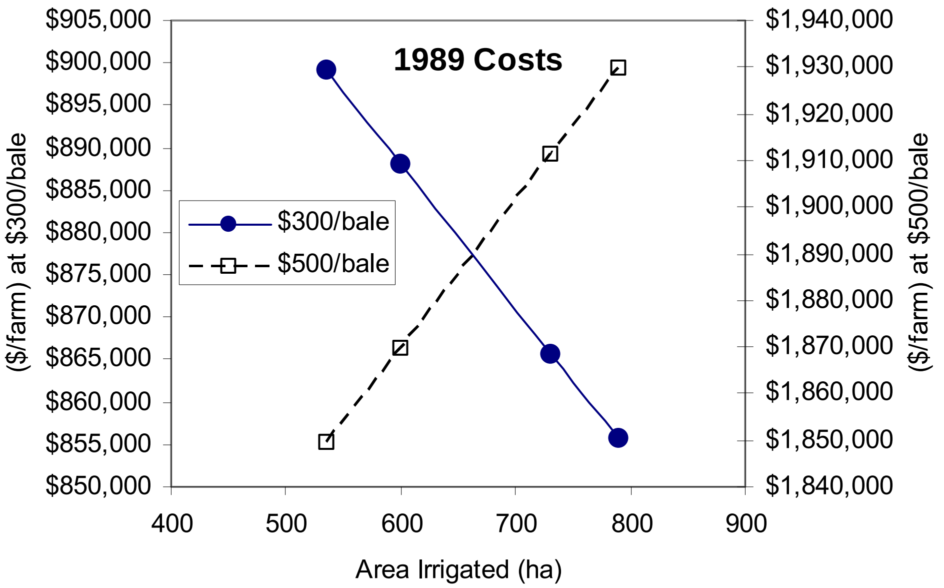


Figure 90 Whole-farm gross margin ($/farm) as a function of area irrigated for an irrigation water allocation of 3000 ML and cotton prices of $300 and $500/bale. Based on 1989 production costs for Emerald, Australia (Keefer, 1989).

The pattern in gross margins, however, will also depend on the proportion of cotton prices to production costs. Although current cotton prices in Australia are comparable to those in 1989, costs of production have changed dramatically. While Keefer (1989) estimated the variable cost of cotton production for 1989 at $900/ha and water charges at $14.85/ML, Wylie (2006) in a recent study estimated the variable cost of cotton production in a hot environment like Emerald's at $2,167/ha and water charges at $40/ML. These represent increases of 141% and 169% in production cost and water charges, respectively. These increases have significantly changed the economics of irrigated cotton production in Australia. These costs, however, are just the variable costs and do not include overhead cost. As stated earlier, the Australian Cotton Comparative Analysis-2005 crop (Newnham et al., 2006) showed cost of cotton production of $4,000/ha for 2004 and $2,949/ha for 2005.

The previous economic analysis was repeated using costs of cotton production and water charges estimates for 2006 as reported by Wylie (2006). Results for 2006 in Table 41 and Figures 91 to 93 show that similarly to 1989, the gross margin per unit area ($/ha) decreased with area irrigated. However, for 2006 the $/ha became even negative for the lower cotton price ($300/bale) when the area irrigated exceeded approximately 650 ha. A similar decreasing patter was observed for the gross margin per unit irrigation ($/ML) and for the whole farm ($/farm). These results suggest that under the assumptions of this analysis for 2006, if water is limited, it is more profitable to fully-irrigate a reduced area than deficit-irrigate a larger area. Notice that in both the 1989 and 2006 scenarios, the option that increased the $/ML also increased the $/farm, which is due to the fact that in the analyses water was the factor limiting production.

Table 41. Economic analysis for cotton under different deficit-irrigation scenarios at Emerald, Australia. Based on the data reported by Keefer (1989), but using cost of production from 2006 as estimated by Wylie (2006) for a hot environment.

Soil water deficit to apply irrigation (mm)	**75 mm**	**100 mm**	**120 mm**	**150 mm**
Water allocation (ML/farm)	3000	3000	3000	3000
Average number of irrigations	6	4	3	2.5
Irrigation Applied (ML/ha)	5.6	5	4.1	3.8
Irrigation efficiency (%)	80	80	80	80
Irrigation infiltrated (ML/ha)	4.5	4.0	3.3	3.0
Maximum crop area (ha)	536	600	732	789
Yield (bales/ha)	8.9	8.2	7.1	6.8
Relative yield (%)	100	92	81	77
Farm Budget:				
Whole farm production (bales/farm)	4752.5	4908.7	5228.8	5369.2
Variable cost ($/ha)	$2,167	$2,167	$2,167	$2,167
Water charge ($/ML)	$40.00	$40.00	$40.00	$40.00
Farm variable cost ($/farm)	$1,160,893	$1,300,200	$1,585,610	$1,710,789
Farm water charge ($/farm)	$120,000	$120,000	$120,000	$120,000
Farm variable costs + water charge	$1,280,893	$1,420,200	$1,705,610	$1,830,789
Crop price ($/bale)	**$300**	**$300**	**$300**	**$300**
Gross income ($/farm)	$1,425,744	$1,472,616	$1,568,646	$1,610,765
Gross margin for whole farm ($/farm)	$144,851	$52,416	-$136,963	-$220,024
Gross margin per unit area ($/ha)	$270	$87	-$187	-$279
Gross margin per unit irrigation ($/ML)	$48	$17	-$46	-$73
Crop price ($/bale)	**$1,200**	**$1,200**	**$1,200**	**$1,200**
Gross income ($/farm)	$5,702,976	$5,890,464	$6,274,586	$6,443,060
Gross margin for whole farm ($/farm)	$4,422,083	$4,470,264	$4,568,976	$4,612,271
Gross margin per unit area ($/ha)	$8,255	$7,450	$6,244	$5,842
Gross margin per unit irrigation ($/ML)	$1,474	$1,490	$1,523	$1,537

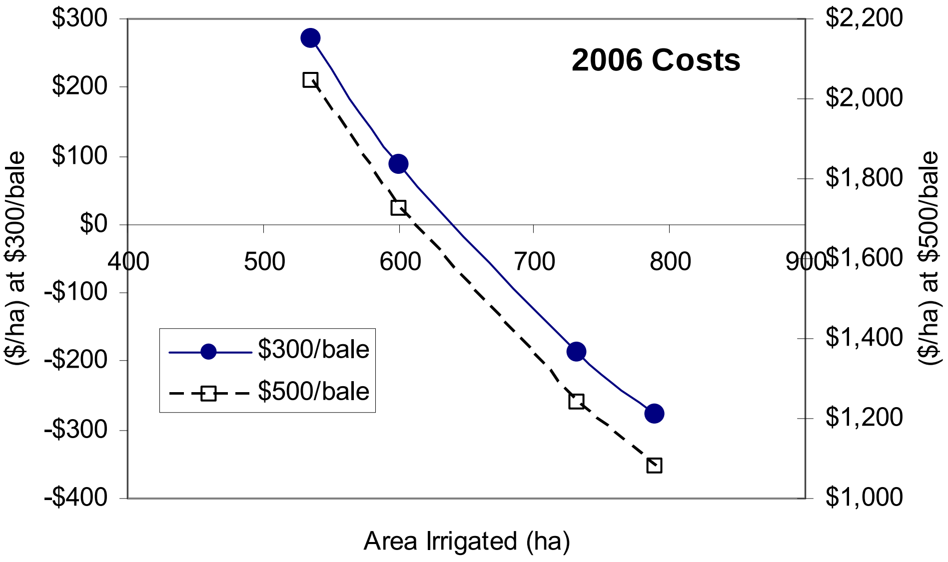


Figure 91 Gross margin per unit area ($/ha) as a function of area irrigated for an irrigation water allocation of 3000 ML and cotton prices of $300 and $500/bale. Based on data for Emerald, Australia, reported by Keefer (1989), and cost of production for 2006 as estimated by Wylie (2006).

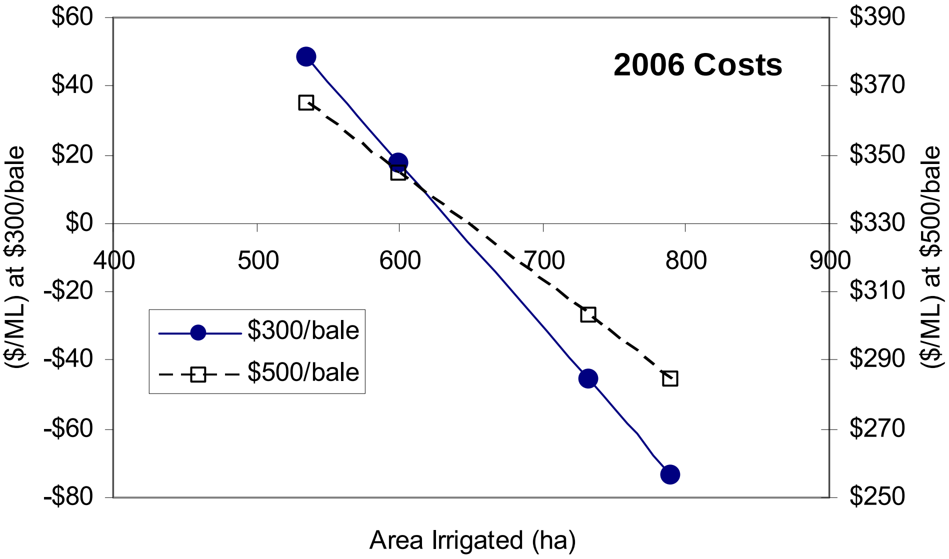


Figure 92 Gross margin per unit irrigation ($/ML) as a function of area irrigated for an irrigation water allocation of 3000 ML and cotton prices of $300 and $500/bale. Based on data for Emerald, Australia, reported by Keefer (1989), and cost of production for 2006 as estimated by Wylie (2006).

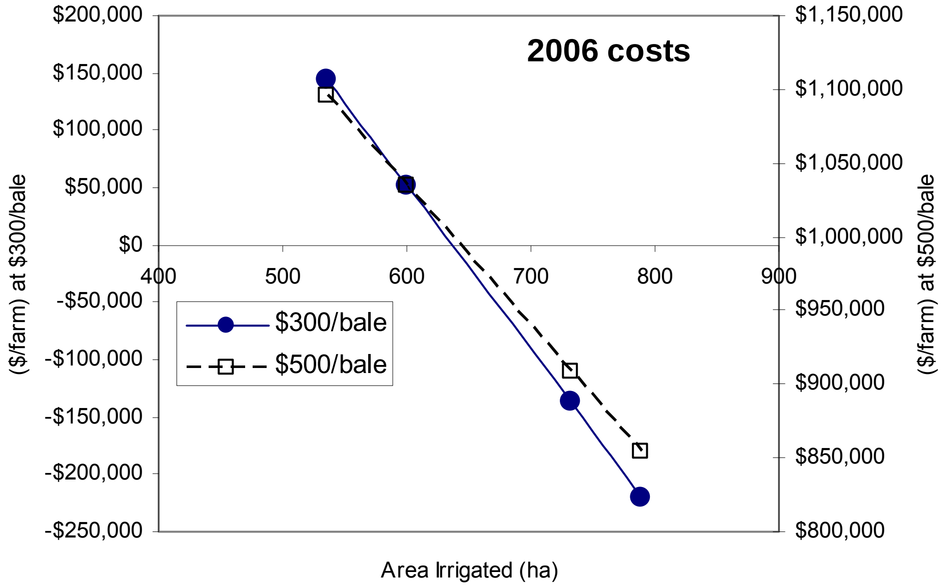


Figure 93 Whole-farm gross margin ($/farm) as a function of area irrigated for an irrigation water allocation of 3000 ML and cotton prices of $300 and $500/bale. Based on data for Emerald, Australia, reported by Keefer (1989), and cost of production for 2006 as estimated by Wylie (2006).

The previous economic analysis is sensitive to changes in costs of production, cotton prices, and the yield versus irrigation response function. For instance, with the 2006 costs of production, and using the same yield versus irrigation response function, a significant increase in cotton price could reverse the slope of the line in Figure 93, resulting in increasing whole-farm gross margin ($/farm) as the area increases. To determine the cotton price at which the slope of the line in Figure 93 would change sign, the whole-farm gross margins ($/farm) were determined for assumed cotton prices ranging from $600 to $1200/bale. The slope of the line of gross margin versus area irrigated (as in figs 90) was then determined for each cotton price. It was found that the slope of the line was linearly related to cotton price (Figure 94). From the equation in Figure 94 [slope = 2.4304(cotton price) - 2167], it can be determined that the slope of the line becomes zero at a cotton price of $892/bale (2167/2.4304 = $892), being negative for lower cotton prices and positive for higher prices. A similar analysis was conducted for the 1989 costs of production, which is shown in Figure 95. Also, from the equation in Figure 95 [slope = 2.4304(cotton price) - 900], it can be determined that for the 1989 costs, the slope of the line becomes zero at a cotton price of $370. This cotton price represents the break-even price above which the whole-farm gross margin ($/farm) can be increased by increasing area irrigated and deficit-irrigating a larger area instead of fully-irrigating a reduced area.

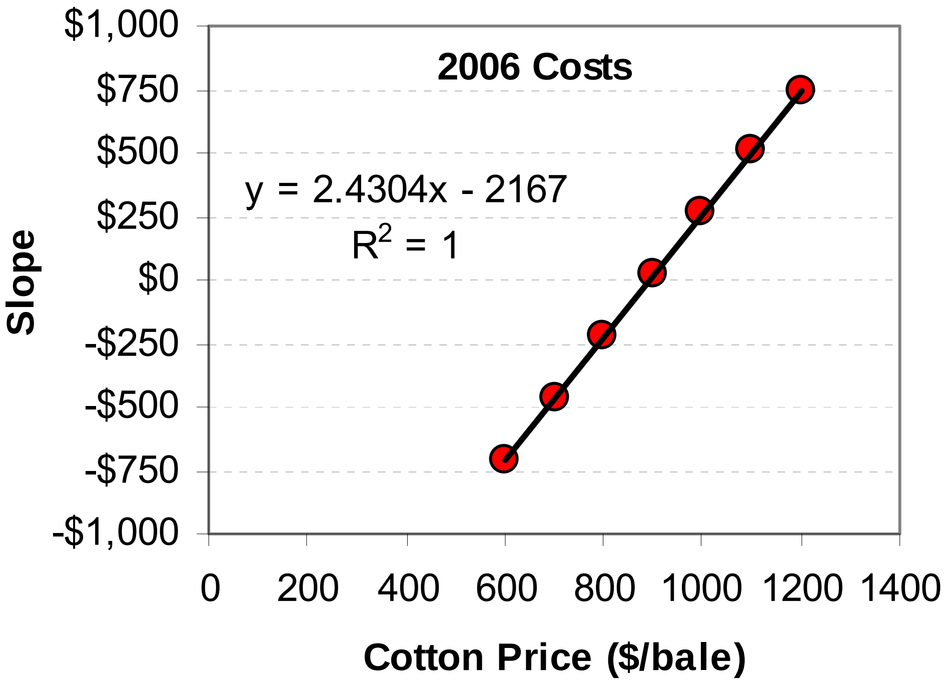


Figure 94 Slope of the line of whole-farm gross margin ($/farm) versus area irrigated, as a function of cotton price for an irrigation water allocation of 3000 ML. Based on data for Emerald, Australia, reported by Keefer (1989), and cost of production for 2006 from Wylie (2006).

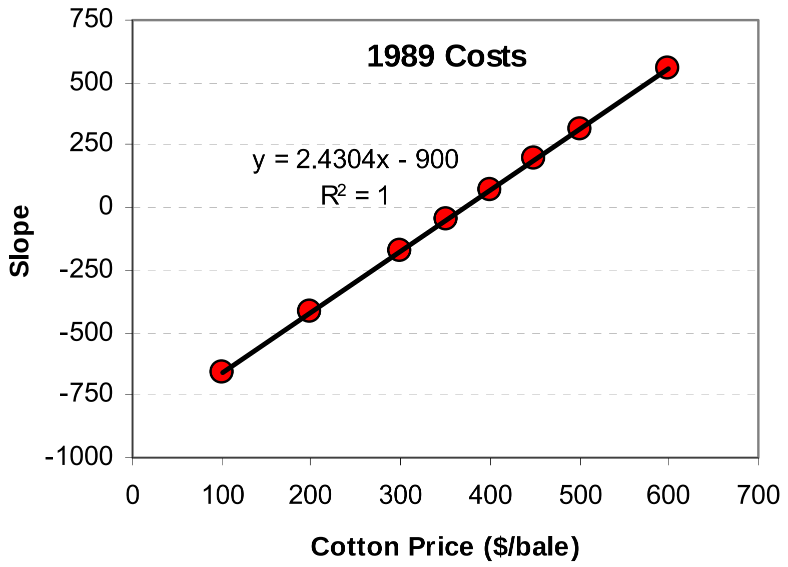


Figure 95 Slope of the line of whole-farm gross margin ($/farm) versus area irrigated, as a function of cotton price for an irrigation water allocation of 3000 ML. Based on data for Emerald, Australia, reported by Keefer (1989), and cost of production for 1989.

Notice that the slopes of the lines in Figure 94 and 95 (2.4304) are the same for the 2006 and 1989 costs. This value actually represents the intercept of the response function of yield versus irrigation infiltrated used in the analysis, and previously shown in Figure 87. This intercept represents the "dryland yield." Also notice that the intercepts of the lines in Fig. 94 and 95 (2167 and 900), are actually the variable costs per unit area ($/ha) (not including irrigation charges), as indicated in Tables 40 and 41. Therefore, the slope of the line of whole-farm gross margin ($/farm) for a given cotton price, dryland yield, and cost of production can be determined as:

$$Slope = (D\_Yield)(C\_Price) - V\_Cost \qquad (3)$$

where, Slope = slope of whole-farm gross margin ($/farm) versus maximum area that can be irrigated (ha) at a level of irrigation (ML/ha) with a given farm water allocation (ML/farm) and irrigation efficiency (%), D_Yield = dryland yield (bales/ha), C_Price = crop price ($/bale), and V_Cost = variable production cost per unit area ($/ha). Therefore, the cotton price at which the slope of the line is zero (C_Price_zero) can be determined as:

$$C\_Price\_zero = (V\_Cost)/(D\_Yield \qquad (4)$$

This equation shows that as the dryland yield increases, there would be less risk involved in increasing area irrigated and deficit-irrigating. Therefore, the "C_Price_zero" at which irrigated area can be increased would be lower. The opposite occurs with the variable cost.

Therefore, in situations where water is limited and there is a fixed water allocation for the farm, the farmer has to decide whether to fully-irrigate a small area or deficit-irrigate a larger area. To increase whole-farm gross margin ($/farm), the logic in Table 42 can be applied.

Table 42 Guidelines to decide whether to increase or decrease area irrigated in order to maximize whole-farm gross margins ($/farm) with a limited water allocation.

Condition	Area irrigated	Irrigation level
(C_Price) > (C_Price_zero)	Increase area	Deficit-irrigate
(C_Price) < (C_Price_zero)	Decrease area	Fully-irrigate
(C_Price) = (C_Price_zero)	No difference	No difference

"C_Price" = crop price, and "C_Price_zero" = crop price at which the slope of the line relating whole-farm gross margin ($/farm) and area irrigated is zero.

Gibb (1995) presented results of economic analysis (conducted by B. Hearn) addressing the question of whether to increase of decrease are planted when water was limited for the different cotton producing areas of Australia. He concluded that:

"The optimum strategy is to reduce the area of crop to allow 5 ML per ha on 1st September in the north and 6 ML per ha in the south. If a larger area is planted in hope of increased supplies before the first irrigation is due, the optimum strategy at the time of first crop irrigation is to reduce the area of crop to allow 3 ML per hectare in the north and 4 ML per hectare in the south."

The previous equations, however, show that this strategy will not always be correct, since the strategy that maximises $/farm depends on cotton prices, production cost, and the dryland yield, which all change with time. However, Gibb (1995) provided simulated yields for different amount of available irrigation water for different cotton producing areas in Australia and an economic analysis providing the percent risk of failing to break even for cotton prices ranging from $350 to $750/bale. The economic analysis, however, did not consider changes in production cost.

In the previous discussion, the focus has been on irrigation. However, the farmer should also consider the dryland alternative. There are situations in which dryland production may be more profitable than irrigated production. Another issue that has not been considered here is that of crop quality and the price premiums or penalties associated with the quality of the final agricultural product. For cotton, for instance, water stress can significantly affect fibre quality (Cull et al., 1981), which may significantly affect economic returns.

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APPENDIX 2

Cotton Water Use Efficiency Study (re-survey of Sunnil Tennakoon and Steve Milroy's 1990s study)

The Cotton Industry is endeavouring to document how on-farm water use efficiency has improved since the original benchmark survey conducted by Sunnil Tennakoon, CSIRO in the 1990s. The aim is to re-survey the original 25 farms and collect field and/or farm level data for two to three seasons since 2000-01. This will enable comparisons to be drawn on how the industry has changed irrigation management in the past decade.

With your co-operation we would like to collect new data for the fields originally surveyed. ***I emphasise that information provided and farm identity will be dealt with in the strictest confidence.***

Property Name ____

Please attach farm map showing fields and their dimensions:

Farm Level

Season	200_/0_	200_/0_	200_/0_
Total area of cotton (ha)			
Total Cotton Production (bales)			
Total Water Pumped (for cotton) from river (ML)			
Total Water Pumped (for cotton) from bores (ML)			
Total on-farm harvested water (ML)			
Storage Water Used (ML)			
Total collected overland flows (ML)			

What practices have you put in place over the last 5 years to improve your WUE?
____

____

____

____

____

Have you used an irrigation consultant? If so, what for specifically? ______

____

____

Are you using precision ag. technology? ______________________________

____

Where do you get your irrigation information from? ___________________

____

____

What soil tillage practices have been carried out? ______________________

In-crop Rainfall Data

200_/0_		200_/0_		200_/0_	
Date	Amount (mm)	Date	Amount (mm)	Date	Amount (mm)

Field Level

Season: ______________________________

Property: ______________________________

Field name: ______________ Field Area: __________ ha

Field slope: ______________ Field length: __________ m

Soil Type: ______________________________

Previous Crop: ______________________________

Sowing Date: ______________ Harvest Date: __________

Lint Yield: ______________ b/ha

Irrigation	Date	Application Depth (mm)
Pre-Irrigation		
Flushing		
1st In-crop		
2nd In-crop		
3rd In-crop		
4th In-crop		
5thIn-crop		
6th In-crop		
7th In-crop		
8th In-crop		
9th In-crop		
10th In-crop		

Soil moisture readings (neutron /capacitance probe data)

Date	Soil Moisture (mm)	Date	Soil Moisture (mm)

What are the typical run length times for siphons?

What size siphons? ____

What siphon configuration do you use?______________________________
(singles, doubles, etc)

When was the field last laser levelled? ______________________________

____

Have you had an EM survey done of the field? _________________________

____

Benchmarking Water Management in the Australian Cotton Industry

April 2008

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Contents

1. Introduction

1.1. Background

Irrigation is an essential concern for Australian agriculture and is particularly important for the cotton industry with over 80% of the land under production being irrigated. Secondly only to pasture, cotton accounts for approximately 16.2% (1,735 GL in 2005-06) of the total water used by agriculture with an average application rate of 6.4 ML per hectare (ABS 2008). As a significant water user, the cotton industry must be able to account for and demonstrate its ability to efficiently utilise Australia's water resources.

Surface irrigation or more precisely, furrow irrigation currently the most predominant technique for broadacre agriculture and will remain to be a viable option for the foreseeable future. Pressurised lateral move and centre pivot irrigation systems have definite advantages over traditional furrow but at the same time are associated with a new series of issues and drawbacks. Rather than adopting a one size fits all approach in relation to system conversion, the industry must realise that a significant proportion of irrigators will continue to pursue furrow irrigation. As a result there will be a ongoing drive from irrigators striving for system optimisation of existing layouts and development of improved irrigation strategies.

1.2. Surface Irrigation Evaluation

Surface irrigation evaluation describes the processes to assess the irrigation performance, namely the proportion of water beneficially used (i.e. water use efficiency) and the "evenness" of the application (i.e. the distribution uniformity). These results can be used to quantify both the economic returns and costs of irrigation and the offsite environmental impacts. In addition, they provide a benchmark to be used to demonstrate the potential benefits of system optimisation or system change.

Irrimate™, developed by the National Centre for Engineering in Agriculture in collaboration with Aquatech Consulting, is one prime example. The Irrimate™ in-field evaluation system encompasses all the tools, software and procedures required to evaluate furrow irrigation. Field evaluation as demonstrated in that system involves the following steps:

1) – Measurement of the total water applied to the field
2) – Collection of in-field measurements including furrow geometry and water front advance
3) – Inverse solution from field measurements to determine the soil infiltration characteristic

4) – Computer simulation (using the information collected in steps 1-3) under the existing field management to evaluate the current performance.
5) – Optimisation of the irrigation by using the simulation model to evaluate changes to the field layout and/or management.

In the cotton industry the practice of field evaluation had been greatly successful over the past decade. Considering Irrimate™ consultants alone there was in excess of 300 evaluations performed prior to and including the 2004-2005 season (Raine et. al. 2005). There is little doubt that field evaluation, and the associated recommendations have been responsible for substantial improvements in water use efficiency across the Australian irrigation sector

1.3. Rationale behind ISID

Although there have been a large number of evaluations performed, it is generally difficult to source reliable information on the current state of the irrigation industry. Since its commercial début in 2001, Irrimate™ has been highly successful; both considering the number of evaluations and the impressive documentable improvements in efficiency. However, the data recording and reporting processes have been managed with different levels of rigour, resulting in large volumes of information with little consistency between individuals or organisations. Consequently it is almost impossible to use this data to conduct industry wide benchmarking of existing performance and demonstrate realised and potential improvements to irrigation performance.

The Irrimate Surface Irrigation Database, known by the acronym ISID was conceived in an attempt to address these issues. Firstly it provides a standard for data recording procedures, including but not restricted to all data required for normal system evaluation. Secondly, and more importantly, ISID is a web-interfaced database which has the capacity to store large numbers of events in a hierarchical organised fashion. It is developed around a secure and proven database structure, ensuring complete anonymity of data between separate users. The complete system allows users to search through all entered evaluations to capture industry snapshots filtered by district, season, soil type and other selected parameters. ISID is designed to collate field measurements and simulation results to facilitate benchmarking of surface irrigation performance at the farm, catchment and industry levels.

1.4. Building on the IPART Approach

The South East Queensland irrigation industry was faced with similar data management issues. Large numbers of evaluations were carried out under the Rural Water Use

Efficiency (RWUE) projects and despite best efforts there was a great difficulty in collation of the resulting measurements.

The Irrigation Performance Audit and Reporting Tool (IPART) was created to assist extension staff, consultants and industry development officers in both the evaluation and collation of field measurements. IPART was developed by the NCEA and funded by the Queensland government through the Department of Natural Resources and Water as part of the South East Queensland Irrigation Futures project. IPART is a web based database that provides standardisation of field collection and data recording procedures (Raine and Curran 2007). The interface has the capacity to perform simple data analysis to compute water use and uniformity indices. The software also includes a reporting feature with the ability to automatically generate recommendations based on the identified system issues. Currently IPART has the capacity to process and record measurements collected from the following:

- Travelling guns and booms
- Side-roll spinklers
- Hand-shift sprinklers
- Solid set sprinklers
- Lateral move and centre pivot machines
- Drip and micro-spray systems

IPART is generic in design and is hence applicable to any pressurised irrigation system regardless of industry or district. Since inception, IPART has been extended to other areas outside south-east Queensland including the cotton industry for centre pivots by the QDPI&F and its adoption by the sugar industry for travelling guns and centre pivots by the Bureau of Sugar Experimental Stations (BSES).

There are clear parallels between the recently completed IPART and the surface irrigation database. As such much of the ideas and principles developed in IPART were directly applicable to ISID. However, there are also some clear differences between the two, mainly due to the procedures involved in evaluating a furrow system. Within IPART, the irrigation performance, namely the distribution uniformity is calculated directly and very simply from the field measurements of water depths/volumes within catch cans. For surface irrigation, the evaluation of irrigation performance requires simulation using an appropriate hydraulic model (e.g. SIRMOD). These models require a description of the soil infiltration characteristic which is estimated using a separate model such as IPARM. Inclusions of this same functionality in the web interface has been flagged for future versions of ISID but the work required was beyond the scope of this project.

1.5. ISID

ISID (Irrimate Surface Irrigation Database) was developed using similar database architecture and using a similar web interface to that of IPART. Despite this, the two remain separate entities with ISID retaining no reliance on IPART. ISID is comprised of a PostgreSQL database coupled with a php scripted web interface. The user manual is available online and details all functions of the software including data capture from the Irrimate analysis models and explanation of the soil classification.

ISID is designed to be fully compatible with the Irrimate™ system. It provides the ability to record and store all data necessary to conduct simulation runs, system evaluation and optimisation using standard Irrimate™ procedures. However, the system is generic and may be equally applied to alternative field measurement techniques and/or software models.

2. Accessing ISID

The Irrimate Surface Irrigation Database (ISID) is designed to assist in the evaluation and collation of data from the Irrimate infield system.

ISID was developed by the National Centre for Engineering in Agriculture at the University of Southern Queensland. This work was funded by the Cotton Catchment Communities CRC (CCC CRC) in collaboration with the Queensland Government through the Department of Primary Industries and Fisheries (QDPI&F).

About ISID...

Figure 2.1 – ISID login screen

2.1. The Web Interface

ISID is accessed through the world wide web using any of the popular web browsers such as Microsoft Internet Explorer, Mozilla Firefox or Netscape Navigator. Currently ISID is located on the NCEA web server and can be found at:

http://139.86.208.170/isid

2.2. Compatible Web Browsers

At the current time ISID has been tested and is fully compatible with Microsoft Internet Explorer versions 6, 7 and 8; Mozilla Firefox 2.0 and Netscape Navigator. Minor differences between browsers resulted in compatibility issues which have been rectified in the final version of ISID. The web interface has been developed to comply with the HTML standards wherever possible and therefore should be compatible with the latest versions of any alternative browser. Those users experiencing problems with alternative web browsers should install one of the following:

- **Microsoft Internet Explorer** – Included within Microsoft Windows XP and Vista.
- **Mozilla Firefox** – A free (open source) browser developed by Mozilla, available from http://www.mozilla.com/en-US/
- **Netscape Navigator** – The once popular but now unsupported web browser http://browser.netscape.com/

3. ISID data requirements

ISID has the capacity to store information describing a large range of field characteristics, management and irrigation performance. The summary statistics currently returned by the database only reference a small proportion of this data. Some additional data fields are used in the filters on the search page.

At the present time a large proportion of the data stored within the database may appear to be redundant. However, the majority of this data is automatically uploaded from model input files at no extra burden on the user and should prove useful for future versions of ISID. The database was developed in such a way that stability is not compromised where individual furrows or evaluations are missing these “optional” pieces of information. Many data fields such as wheeled/non-wheeled furrow have a “not recorded” option to be selected in those cases where the user cannot access the appropriate information. The complete irrigation record provides a wealth of information to the user and facilitates tracking of previously entered evaluations. The collection of this additional data does not greatly increase the time burden on the user as the majority of the numerical values are uploaded automatically from the simulation input files.

The data required by ISID is covered in detail in the user manual, those interested should consult this document. The information here is provided merely as a brief summary. Irrigation records are stored within ISID using a hierarchal structure (Figure 3.1) starting with the ***Evaluation*** at the top level. The evaluation groups all evaluations performed on a particular field during a single cropping season. The evaluation owns any number of events where each ***event*** is a different irrigation with a unique date. At the bottom level, each event posses a given number of furrows; the ***furrow*** stores the measurements and simulation data relating to a single furrow. The “edit evaluation” page displays all information relating to a single evaluation, i.e. all events and furrows monitored for that site for a single season.

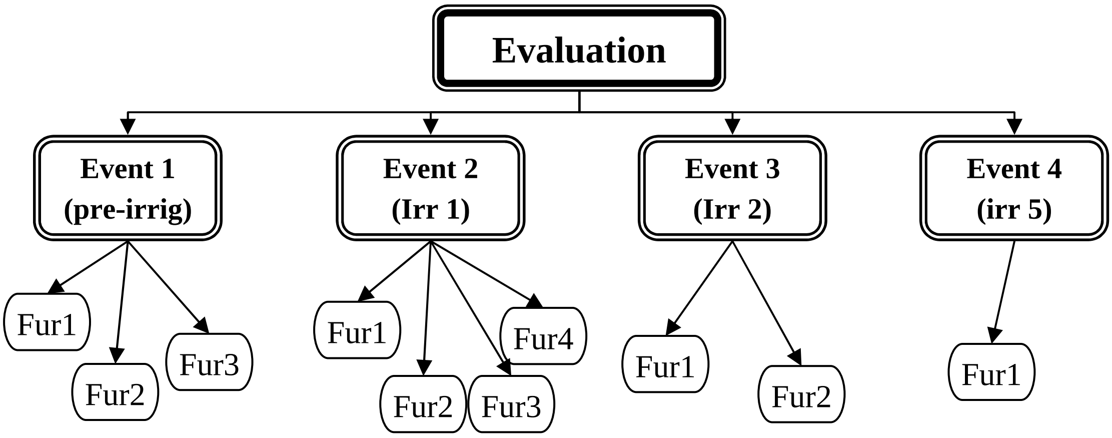

Figure 3.1 – Hierarchical tree structure for furrows within an evaluation

3.1. Property/Field Level Information

The property and field level data (Figure 3.2) is common to all furrows for a particular evaluation and is therefore entered once. Much of this data is used for identification purposes only and is not visible to anyone other than the user entering the data. This section contains three parts:

- **Grower contact:** name[*], phone number and address.
- **Property location:** name[*], address
- **Field:** name[*], district[*], lat/long, field length, field width, slope and soil type[*]

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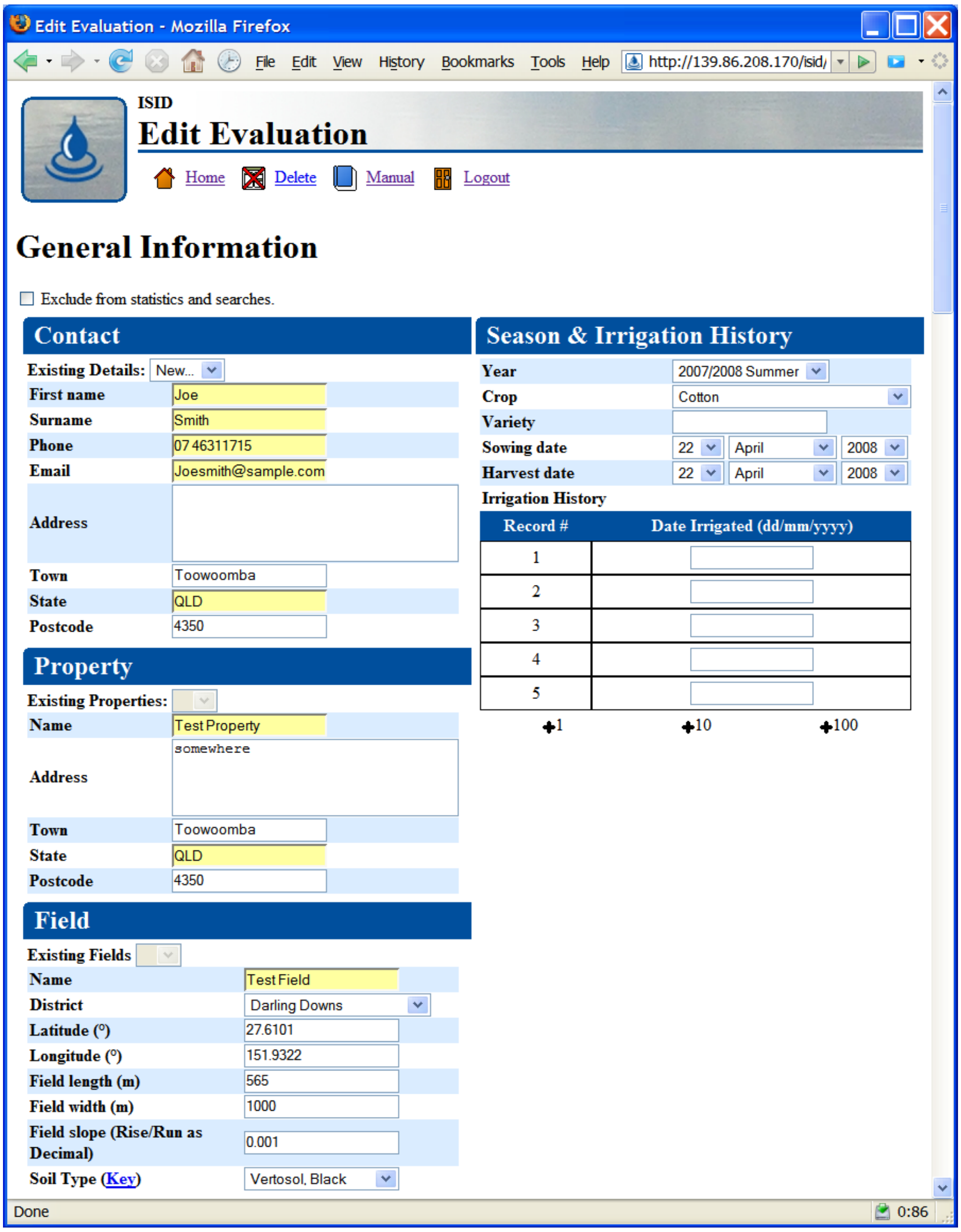
[*] Required data fields



ISID

Edit Evaluation

Home Delete Manual Logout

General Information

☐ Exclude from statistics and searches.

Contact

Existing Details:	New...
First name	Joe
Surname	Smith
Phone	07 46311715
Email	Joesmith@sample.com
Address	
Town	Toowoomba
State	QLD
Postcode	4350

Property

Existing Properties:	
Name	Test Property
Address	somewhere
Town	Toowoomba
State	QLD
Postcode	4350

Field

Existing Fields	
Name	Test Field
District	Darling Downs
Latitude (°)	27.6101
Longitude (°)	151.9322
Field length (m)	565
Field width (m)	1000
Field slope (Rise/Run as Decimal)	0.001
Soil Type (Key)	Vertosol, Black

Season & Irrigation History

Year	2007/2008 Summer
Crop	Cotton
Variety	
Sowing date	22 April 2008
Harvest date	22 April 2008

Irrigation History

Record #	Date Irrigated (dd/mm/yyyy)
1	
2	
3	
4	
5	

+1 +10 +100

Figure 3.2 – Edit evaluation, Property/Field information

3.2. Field Measurements

Following the tree structure (Figure 3.1), the field measurements are divided into the event information and the furrow information. The event data (Figure 3.3) prompts the user to select the irrigation number and date. Often there are differences in interpretation of the irrigation number, some start numbering from the first irrigation, some start numbering after planting whilst others include a "pre-irrigation" and "wetting up" irrigation (immediately after planting) and start numbering from the next irrigation. ISID has adopted a the numbering scheme where the pre-irrigation is the first irrigation before crop planting and the in-season irrigations commence at number 1 after planting. This should clear up any differences and allow ISID to effectively remove/include the pre-irrigation in the calculation of the summary statistics. The post recommendation option aims to differentiate between those irrigations which are/are not managed according to previous Irrimate optimisations. Once the data base contains a sufficient number of evaluations this information can be used to demonstrate the realised benefits of the Irrimate service.


Events

Event 1

Irrigation Number	Preirrigation
Date	20 September 2007
Post Recommendation?	(Not Recorded)
Extra information	This is a test evaluation

Figure 3.3 – Event data entry

An event can contain any number of measured furrows, where each furrow has unique values for all of the field, infiltration, and performance characteristics. The furrow data contains:

- **Furrow dimensions[*]:** field length[*]; slope; furrow spacing[*]; top, mid, bottom widths and height
- **Furrow type:** i.e. every furrow/alternate furrow/bed
- **Upstream measured condition:** depth, area, assumed Manning roughness
- **Inflow:** inflow rate[*], time to cut off[*], variable/constant inflow
- **Runoff:** measurement position, start time, stop time
- **Moisture Deficit[*]:** moisture deficit[*] and source (guess, ETo, Probe)
- **Siphon Info:** number and size
- **Advance Data:** data table imported from Infilt/IPARM file
- **Inflow Data:** data table imported from IPARM file
- **Runoff Data:** data table imported from IPARM file
- **Infiltration Parameters:** a[*],k[*],f_0[*] and calculation method

3.3. Simulation Results

The simulation results section, provided for each furrow is crucial to the generation of the summary statistics and hence it is important that it is completed. It is anticipated that the majority of ISID users will be familiar with the simulation model SIRMOD (Walker 2003). The simulation results section (Figure 3.4) is designed to allow direct entry of all required information straight from the main SIRMOD interface. Additional results used in the summary statistics such as the averaged applied depth, deep drainage, infiltrated

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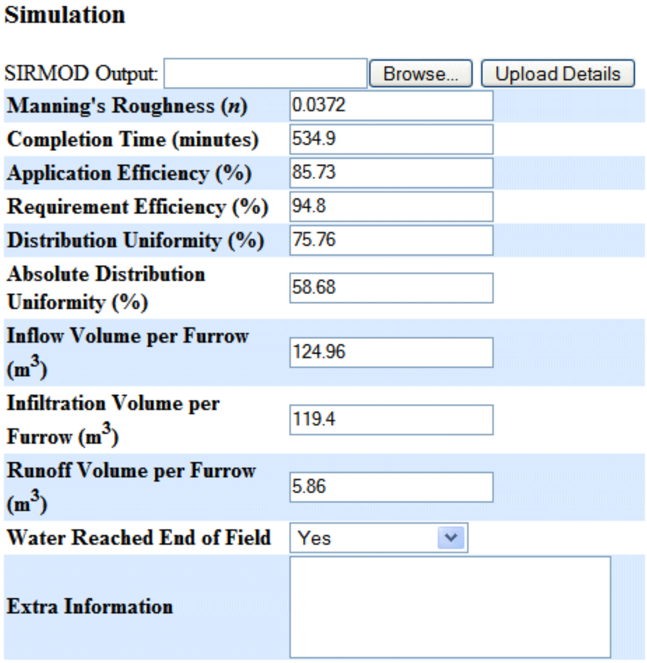
[*] Required data fields

depth are calculated based on the data entered here combined with selected characteristics from the measured data section (e.g. field length, inflow rate and furrow spacing).



Manning's Roughness (*n*)	0.0372
Completion Time (minutes)	534.9
Application Efficiency (%)	85.73
Requirement Efficiency (%)	94.8
Distribution Uniformity (%)	75.76
Absolute Distribution Uniformity (%)	58.68
Inflow Volume per Furrow (m^3)	124.96
Infiltration Volume per Furrow (m^3)	119.4
Runoff Volume per Furrow (m^3)	5.86
Water Reached End of Field	Yes
Extra Information	

Figure 3.4 – Simulation results data entry

ISID also has the capacity to capture a second series of simulation results for the “optimised” performance. This section, titled Recommended Management stores the altered values of inflow rate/cut off time and field length combined with the simulation results under this proposed management. Currently ISID does not have the capacity to automatically optimise a given furrow; hence entry of the recommended management is up to user discretion.

3.4. Data Upload

ISID includes a large volume of field characteristics and simulation results for each furrow. The manual entry of all required values is a tedious and time-consuming process which may also involve a degree of data entry errors. Much of the data requested by ISID is already required by the standard software packages included in the Irrimate procedures. Hence, the same data is saved within the input files of those computer programs. To simplify data entry, ISID includes the capability to upload files from InfiltV5, IPARM and SIRMOD II which combined supply the majority of data fields contained within ISID.

INFILT

Infilt input files, with *.dat extension contain all information required to estimate the soil infiltration function from advance data. These files include values for the average inflow rate, cross-sectional flow area and table of advance distances and times.

IPARM

IPARM input files, with *.iprm extension store all information required to estimate the soil infiltration parameters via the IPARM method and hence contain all data provided by the Infilt file with the inclusion extra information. IPARM files contain values for the field length, slope, furrow dimensions, Manning roughness, average inflow rate, runoff start time, advance distances and times and the inflow and runoff hydrographs.

SIRMOD input files

SIRMOD input files, with the *.cfg extension contain values for the field length, slope (can be variable), furrow dimensions, furrow spacing, average inflow rate, cut-off time, moisture deficit and Manning roughness. These files also store the three parameters of the Modified Kostiakov function used to describe the time dependent soil infiltration rate.

SIRMOD output files

SIRMOD output files, with the *.out extension include all simulation results required by ISID. *.out files contain the advance completion time, application and requirement efficiencies, distribution and absolute distribution uniformities and inflow, infiltration and runoff volumes.

InfiltV5 and IPARM both fulfil the same procedure and hence an evaluation will usually only involve use of one or the other. Hence users should either load 1 Infilt and 1 SIRMOD input file or 1 IPARM and 1 SIRMOD file for each furrow. Depending on the windows settings, some users may find it difficult to distinguish between the different files during the upload process. The file upload dialog box does not include a search filter and hence will show all files within the current folder. Those having difficulties should consult the user manual.

4. Security and Data Confidentiality

Access to ISID is controlled using a secure login system. A user is only granted access to the database after entering a valid username and password. ISID contains two different levels of access, the field technician/grower level and the overview or summary level.

A field technician/grower access allows the user to create new and edit existing evaluations. In addition, they are able to perform searches and statistical analysis across the evaluations they themselves have entered. The users at this level do not have any access to the data entered by other users and cannot generate summaries based on the information from any other user. Any evaluations saved by the user are stored on the ISID database and are available to the calculation of summary statistics. However, the user has the ability to exclude evaluations from the database whilst still retaining all information on the server. This is useful for those evaluations that are only part completed or those that are merely test evaluations created while learning how to use the system.

The overview access level enables the user to perform analysis of all data contained within the database (except those excluded evaluations) entered by all users. ISID features measures to maintain confidentiality during calculation of these statistics. The users at this level are only permitted to view summary data calculated from a number of events. They have no access to data relating to the field locations and cannot interrogate the database to obtain input data or simulation results of a particular field or property. In some cases the combination of search options may enable an overview user to present the results of an individual event. ISID ensures confidentiality by only displaying the summary statistics where the current search criterion contains more than a specified number of events (currently 3).

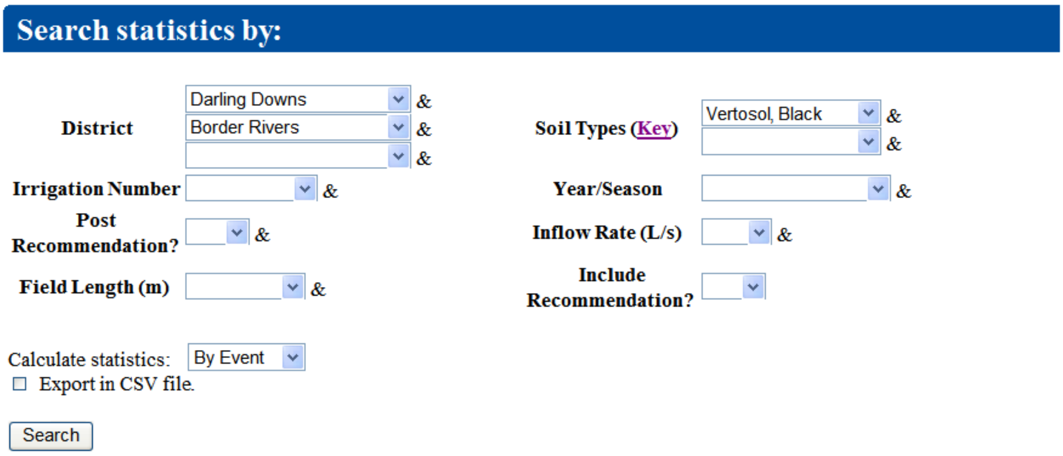
5. Water Use Statistics

5.1. Explanation

Summary statistics can be generated from the technician and overview level homepages, the major differences being that the overview user can search all evaluations while the technician type user can only search evaluations they have entered themselves. Search filters enable the user to investigate the irrigation performance indices for a subset of the database. At the present time the results may be filtered using:

- **District** – splitting the fields into cotton growing regions such as the Darling Downs, Gwidyr, Upper Namoi etc.
- **Soil Type** – according to the Australian Soil Classification
- **Irrigation Number** – Pre irrigation or 1st, 2nd, 3rd, incrop irrigation.
- **Season** – i.e. Summer 2007-2008
- **Post Recommendation** – Is the irrigation managed according to a previous Irrimate recommendation
- **Inflow Rate** – low (0-2 L/s), medium (2-4 L/s) or high flow (>4 L/s)

- **Field Length** – short (0-500 m), medium (500-1000 m), long (1000-1500 m) or extra long (>1500 m).
- **Includes Recommended** – To allow direct comparison of the simulated (measured) and optimised irrigation performance.



Search statistics by:

District: Darling Downs & Border Rivers &

Soil Types (Key): Vertosol, Black &

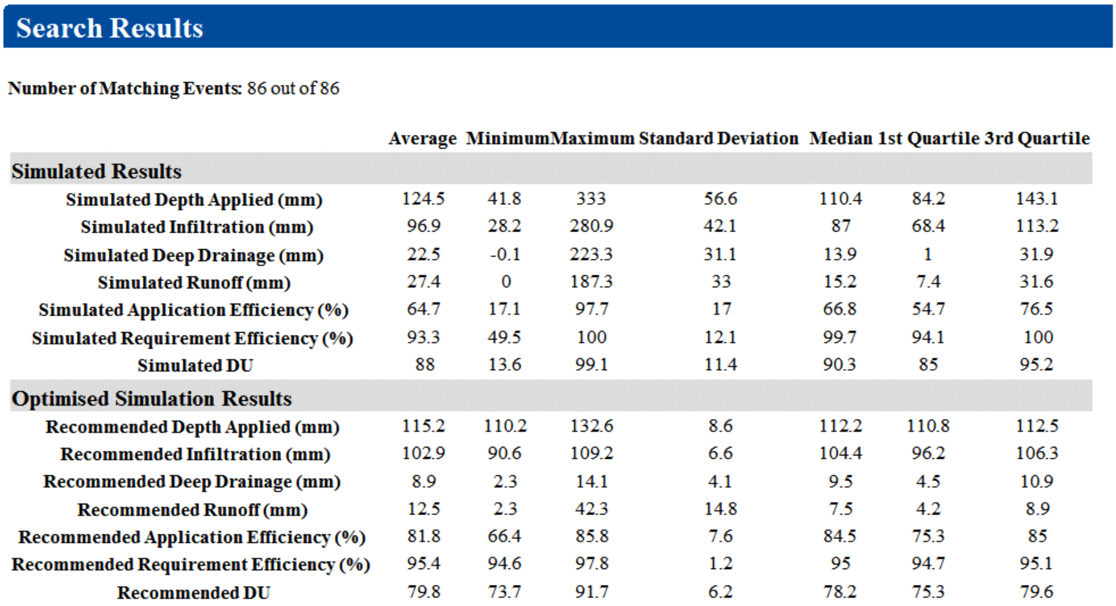
Calculate statistics: By Event

☐ Export in CSV file.

Figure 5.1 – Summary results search filters

Users may select any number of filters for a particular search, selecting a value for one input will display a new drop down box to enable entry of an additional search filter if required. The example shown on Figure 5.1 will return all events within the Darling Downs and Border Rivers conducted on fields with a Black Vertosol soil type. The *Calculate Statistics: By Event/By Furrow* option determines whether the results are calculated by splitting the evaluations into separate furrows or separate evaluations. The statistics returned will always differ between the two whenever events contain more than a single furrow. The "*By Event*" is recommended as it weights each event equally during the calculation process as in contrast to the "*By Furrow*" option which will be biased towards those events with increased numbers of furrows.

The results are split into two sections, one being the simulation results conducted under measured irrigation conditions and the other being the simulation under an "optimised" or user suggested management strategy. The example shown in Figure 5.2 displays the summary statistics for all data included within the database. The results provide an indication of the number of events matching the search filters and included in the statistics compared to the total number currently within the database. ISID also includes the ability to export the summary statistics to a csv text file which can be opened within spread sheet applications (e.g. Microsoft Excel) or text editing software (e.g. notepad).



Search Results

Number of Matching Events: 86 out of 86

	Average	Minimum	Maximum	Standard Deviation	Median	1st Quartile	3rd Quartile
Simulated Results							
Simulated Depth Applied (mm)	124.5	41.8	333	56.6	110.4	84.2	143.1
Simulated Infiltration (mm)	96.9	28.2	280.9	42.1	87	68.4	113.2
Simulated Deep Drainage (mm)	22.5	-0.1	223.3	31.1	13.9	1	31.9
Simulated Runoff (mm)	27.4	0	187.3	33	15.2	7.4	31.6
Simulated Application Efficiency (%)	64.7	17.1	97.7	17	66.8	54.7	76.5
Simulated Requirement Efficiency (%)	93.3	49.5	100	12.1	99.7	94.1	100
Simulated DU	88	13.6	99.1	11.4	90.3	85	95.2
Optimised Simulation Results							
Recommended Depth Applied (mm)	115.2	110.2	132.6	8.6	112.2	110.8	112.5
Recommended Infiltration (mm)	102.9	90.6	109.2	6.6	104.4	96.2	106.3
Recommended Deep Drainage (mm)	8.9	2.3	14.1	4.1	9.5	4.5	10.9
Recommended Runoff (mm)	12.5	2.3	42.3	14.8	7.5	4.2	8.9
Recommended Application Efficiency (%)	81.8	66.4	85.8	7.6	84.5	75.3	85
Recommended Requirement Efficiency (%)	95.4	94.6	97.8	1.2	95	94.7	95.1
Recommended DU	79.8	73.7	91.7	6.2	78.2	75.3	79.6

Figure 5.2 – Summary statistics of all events as of April 2008

The values such as applied, infiltration, deep drainage and runoff volumes are presented in terms of mm depth. This facilitates direct comparison of these quantities across fields with different furrow lengths and wetted furrow spacing. The conversion of units from mm depth to ML per hectare can be performed simply by dividing by 100. For example the average depth applied in Figure 5.2 of 124.5 mm corresponds to 1.245 ML/ha

It is important to note that the “Optimised Simulation Results” cannot be directly compared with the simulated results. A large number of events will not include optimised results therefore the two sets of performance indices will almost always be based on different number of measured events or furrows. To perform valid comparisons the user must select “YES” from the “Includes Recommendation” search filter which will only display the simulated results for those furrows that include a recommended simulation.

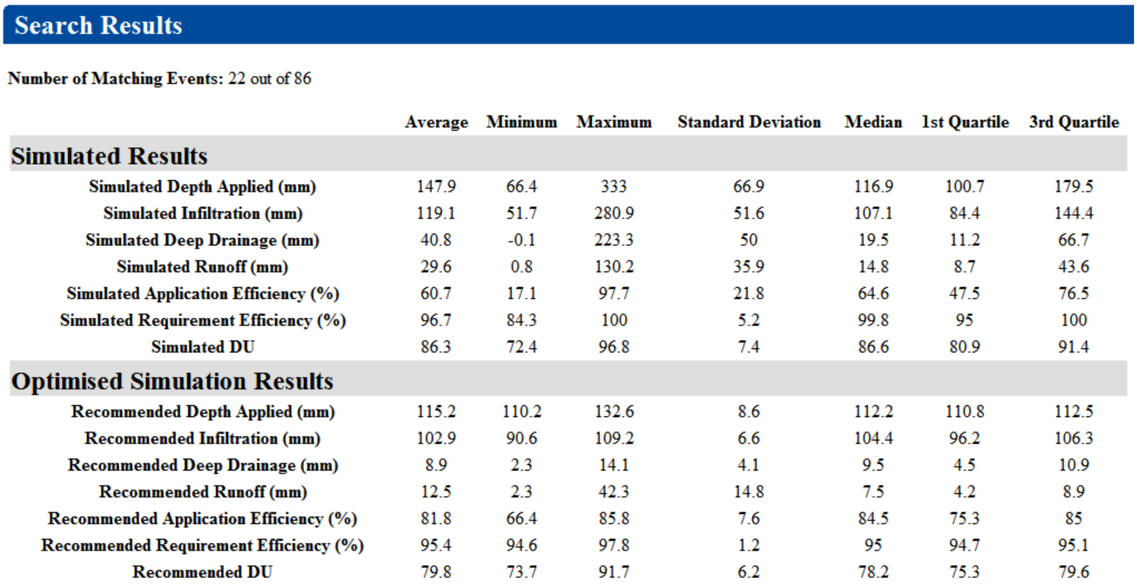
5.2. Case Studies

At this stage the database contains a bare minimum of evaluations hence no conclusions can be drawn from the summary results. The case studies presented here are only used to illustrate the potential of ISID.

Irrigation performance for a particular soil type

ISID can be used to indentify the performance of surface irrigation across all regions on a given soil type. The results in Table 1 were created by selecting “Black Vertosol” for the soil type filter on the search page. Here the number of matching events is 22 out of the total 86 events stored in the database.

Table 1 – Results summary for Black Vertosol soil



Number of Matching Events: 22 out of 86

	Average	Minimum	Maximum	Standard Deviation	Median	1st Quartile	3rd Quartile
Simulated Results							
Simulated Depth Applied (mm)	147.9	66.4	333	66.9	116.9	100.7	179.5
Simulated Infiltration (mm)	119.1	51.7	280.9	51.6	107.1	84.4	144.4
Simulated Deep Drainage (mm)	40.8	-0.1	223.3	50	19.5	11.2	66.7
Simulated Runoff (mm)	29.6	0.8	130.2	35.9	14.8	8.7	43.6
Simulated Application Efficiency (%)	60.7	17.1	97.7	21.8	64.6	47.5	76.5
Simulated Requirement Efficiency (%)	96.7	84.3	100	5.2	99.8	95	100
Simulated DU	86.3	72.4	96.8	7.4	86.6	80.9	91.4
Optimised Simulation Results							
Recommended Depth Applied (mm)	115.2	110.2	132.6	8.6	112.2	110.8	112.5
Recommended Infiltration (mm)	102.9	90.6	109.2	6.6	104.4	96.2	106.3
Recommended Deep Drainage (mm)	8.9	2.3	14.1	4.1	9.5	4.5	10.9
Recommended Runoff (mm)	12.5	2.3	42.3	14.8	7.5	4.2	8.9
Recommended Application Efficiency (%)	81.8	66.4	85.8	7.6	84.5	75.3	85
Recommended Requirement Efficiency (%)	95.4	94.6	97.8	1.2	95	94.7	95.1
Recommended DU	79.8	73.7	91.7	6.2	78.2	75.3	79.6

Event based compared to Furrow based results

Currently there are a total of 86 events with a total of 245 furrows in the database. The results in Table 2 were generated to compare the results between event based and furrow based performance statistics. Where an event contains more than one measured furrow, the event based values are generated by first taking the median of the furrows within each event so that each event possesses a single value of each of the performance statistics. In contrast the furrow based values are calculated directly from the entire 245 furrows. As shown in Table 2 the furrow based results will always provide greater ranges for each performance statistic reflected in the larger difference between min and max and the 1st and 3rd quartiles. It is also important to note that he median and average also differ between the two results. As recommended in the manual, all users should opt for the event based statistics unless they fully understand the difference between the two.

Table 2 – Event based vs furrow based results

		Ave.	Min.	Max.	St. Dev	Median	1st Quart	3rd Quart
Event Based	Deep Drainage (mm)	22.5	-0.1	223.3	31.1	13.9	1.0	31.9
	App. Efficiency (%)	64.7	17.1	97.7	17.0	66.8	54.7	76.5
	Dist. Uniformity (%)	88.0	13.6	99.1	11.4	90.3	85.0	95.2
Furrow Based	Deep Drainage (mm)	23.4	-0.3	237.4	29.9	15.3	0.2	35.3
	App. Efficiency (%)	64.6	17.1	100.0	17.7	66.7	54.3	78.7
	Dist. Uniformity (%)	86.7	3.6	100.0	12.6	90.0	82.4	95.2

Measured compared to improved irrigation management

Select “Yes” in the “includes recommendations” filter, the resulting search yields only 6 events. The results, presented in Table 3 demonstrate the potential increase in performance by implementing the proposed changes to the irrigation management. Across the 6 furrows considered the improved management lifts the average application efficiency from 80.2% to 81.8% and reduces the deep drainage loss from an average of 20.1 mm to 8.9 mm.

Table 3 - Comparison of simulated vs improved performance

	Measured		Improved		Difference (%)	
	Average	Median	Average	Median	Average	Median
Applied (mm)	120.0	114.7	115.2	112.2	-3.97	-2.17
Infiltration (mm)	112.8	110.1	102.9	104.4	-8.81	-5.21
Deep Drainage (mm)	20.1	14.2	8.9	9.5	-55.93	-33.46
Runoff (mm)	7.6	6.2	12.5	7.5	64.48	21.24
App. Efficiency (%)	80.2	83.1	81.8	84.5	1.95	1.73
Req. Efficiency (%)	93.8	95.4	95.4	95.0	1.69	-0.42
Dist. Uniformity (%)	77.3	76.5	79.8	78.2	3.20	2.25

6. Proposals for Future Development

Throughout the developmental phases of ISID, several areas were identified for possible future development. The concepts below are of some interest to the NCEA but are well beyond the scope of the current project. Implementation of the features proposed in this section would require significant further development and funding.

6.1. Storage of Model Input Files

In an attempt to automate the data entry process, ISID includes the capability to upload the input files of InfiltV5, IPARM and SIRMOD. The interface extracts all required data elements from these files but does not actually store the file itself. Consequently, the original input files must be retained or new files may be created by manually copying model parameters from the “edit evaluation” page. ISID does not have any ability to re-generate the original files that were originally uploaded. It is not suggested that ISID will replace existing recording procedures. However, it may still be of great benefit to some users if it is possible to re-create the original input files. Inclusion of this feature within ISID is relatively simple and would require minimal further work. File re-creation could be performed using the same procedure as adopted by IPARM for SIRMOD files. Here a default or “dummy” file is stored on the hard drive is opened and altered by adding specific model inputs. ISID would open the dummy file, insert the known pieces of information and then prompt the user for a new save location. The process would be further simplified for Infilt and IPARM files as they are ASCII text files and hence could be exported directly over the web.

6.2. Integration with Irrimate™ Tools

One major deficiency of the current series of Irrimate™ tools is that they do not interface directly with the analysis software. Users are required to download the data from the in-field tools, upload to a personal computer, process the data and manually enter the necessary measurements into Infilt, IPARM and SIRMOD. The data files produced by the advance sensors and inflow and runoff meters usually conform to a standard format and are saved within a comma or space delimited text file. While it is possible to write code to understand the data contained within these files there are instances where the file may take on a slightly different form. Often the measurements from a single furrow or set of furrows may be spread across multiple files or a single file may contain more than a single irrigation. One major problem is the issue of reset times. Commonly the user must check and modify the reset times to make sure that the irrigation start times match between the inflow, advance and runoff data.

A new series of Irrimate™ in-field tools is currently under development, with the primary purpose of being able to download remotely to a central data collection unit. Release of the new tools facilitates development of a new data recording standard to streamline transfer of the files into the analysis software and ultimately into ISID.

One potential solution to this problem is to include some form of data upload and processing facility within ISID. This approach would ask the user to upload the raw unprocessed data files, require some form of checking process and then have the ability to either perform online analysis of infiltration rates and irrigation performance or produce the required Infilt/IPARM and SIRMOD files for the user to analyse independently to ISID. Alternatively it may be easier to develop a stand-alone application for the user’s computer which can process the raw data and communicate with the ISID database.

6.3. Automated Simulation

ISID does not include any form of simulation capability and as such must rely on manually operated SIRMOD runs in order to generate values for the performance parameters. SIRMOD applies the full hydrodynamic Saint Venant equations to describe the flow of water along the length of a single furrow. When supplied with a known infiltration function SIRMOD will predict the water advance speed, total volumes of infiltration, runoff and deep drainage and the moisture profile across the length of the field. SIRMOD and other simular models can execute a single simulation in a matter of seconds. However, this speed may not be sufficient for ISID as the simulation of one user may consume all resources of the web server during this time. The capacity of the web server for simulation is not yet known. One concern is the need for user intervention in those cases where the simulation does not converge, often the user must alter the numerical parameters in order to complete a successful simulation. Most of these issues could be resolved by the development of a new purpose built simulation model. The development of the automated online simulation would require significant further work.

6.4. Automated Optimisation

One major problem associated with the inclusion of the “Optimised” results is the reliance on the user to manually provide the optimal strategy. This does have some advantages, i.e. it prevents the optimal management from using unrealistic combinations of the inflow rate and time to cut-off. But as a result the suggested optimal strategy is unlikely to reflect the true potential optimal performance.

Probably the most important issue associated with the optimised results is the ability to define the optimisation objective function. The term “optimal” implies that a unique solution exists when in reality the inflow rate/cutoff time combination takes on infinite possibilities dependent on the adopted optimisation strategy (Gillies 2008).

Development of the automated optimisation is dependent on and cannot proceed without the implementation automated simulation. The optimisation process, as currently conceived would require the web server to conduct a large number of simulation runs for each furrow. This may present significant problems for the web server, an optimisation being performed by one user may utilise all server resources and prevent other users from accessing ISID at the same time. However, it may be possible to reduce the computational requirements of the simulation model through a re-design of the numerical scheme.

The alternative to automated online simulation is to develop a model that can link with the database, extract the necessary details and conduct the simulation runs required offline. Once finished the results could be uploaded to the original database. This procedure could be performed at regular intervals and be restricted to those evaluations that have been changed since the last optimisation. The only problem with this approach is the unavoidable delay between data entry and the next scheduled optimisation. Inclusion of this type of optimisation would be of limited benefit to the individual user but would greatly improve the completeness of the summary results.

6.5. Additional "Optimised" results

ISID contains one possible optimised/recommended strategy for each furrow, which may or may not be practically achievable. It would be more appropriate to include multiple optimal strategies which can be compared in the summary statistics:

1) Recommended management – the manually optimised results (those currently included)
2) Optimising Time to Cut-Off – optimising the irrigation performance by changing only the inflow duration
3) Optimising inflow – optimising the irrigation performance by altering both the inflow rate and inflow duration.

Population of these optimised results would require considerable additional effort by the user and is therefore somewhat dependent on the automated optimisation.

7. Recommendations

During this project the NCEA has indentified the following areas for further attention. It is believed that each should be addressed in order for ISID to perform to full potential.

7.1. Data Entry

ISID provides an efficient platform for data collation and storage but relies entirely on individual users entering large numbers of irrigation evaluations. The current version of ISID does not offer any significant advantage for the standard field evaluation. Instead the real value of the system is to provide benchmarks across multiple properties and irrigation districts. It is likely that implementation of some of the proposed changes in section 6 will provide functionality over and above the existing Irrimate procedures and hence serve as a catalyst for use of ISID. Until this occurs the data entry process will remain reliant on the diligence of users to upload and update the necessary information.

It is perceived that the entry of past irrigation data and that of future evaluations will require funding to support a person to enter the required data. The NCEA is independent of all consultants and government agencies and hence is ideally positioned as the provider of this service. It is also important to note that all Irrimate consultants are contractually obliged to provide irrigation data to the NCEA.

7.2. Data Quality Control

Like all computer based systems, ISID is subject to the garbage in garbage out principle. The quality of the results and summary statistics is dependent on the quality of all data supplied to the system. Currently ISID does not contain any quality control measures apart from excluding those furrows with missing or incomplete information. Each user has complete control over the evaluations they have entered is responsible for ensuring the accuracy of all included information. The system administrator, while having control over user accounts does not have access to the entered evaluations. These measures ensure complete data confidentiality but may cause problems when data quality becomes an issue.

Data quality control issues can be addressed by one or a combination of:

1) Providing training to ensure that users are proficient in use of the system.
2) Permitting access of an administrator or data supervisors to the data to identify and fix any problems.

The required administrative workload would be greatly diminished where all users are sufficiently trained. As an alternative to the single administrator model this data checking role could be designated to a “supervisor” within each organisation. The supervisor would have access to a group of general users which would become their responsibility.

7.3. Revision of the Soil Classification Information provided in SOILpak

The document: “SOILpak for cotton growers” (McKenzie 1998) provides a practical and comprehensive description of the soils most commonly found in the cotton growing regions of Australia. Unfortunately SOILpak focuses primarily on the Great Soil Group classification scheme which is not ideally suited to Australian conditions and is being superseded by the Australian Soil Classification (Isbell 1996). The Australian Soil Classification (ASC) promises to rectify the issues of the existing schemes and is uniquely designed for Australian conditions based on a database of over 14000 soil profiles across all states (Isbell 1996). The original database is slightly biased towards Queensland and focuses primarily on agricultural soils, one common criticism of the scheme but no issue for use within ISID or SOILpak.

The ASC is a hierarchical system with mutually exclusive classes based on soil attributes relevant to land use management and applicable across all soils found within Australia. Classification is based on the physical and chemical properties of soil horizons rather than being determined by geographical position or parent materials (Isbell et al. 1997). Soils are assigned names using a classification key which has the major strength of the possibility of indentifying a new unknown soil through a logical process of elimination.

Material is provided within the ISID user manual to help users identify the appropriate ASC soil order and sub-order for a given soil type. An abbreviated soil key can be accessed directly from the edit evaluation page by clicking the appropriate link next to the soil type information. Also found in the user manual is a table demonstrating how the soils from alternative schemes relate to the ASC, including the nomenclature used within SOILpak.

It is strongly suggested that Part E of SOILpak for cotton growers, more specifically Chapter E1 – "*Australian Cotton Soil*" should be modified and updated to properly describe cotton growing soils in terms of the Australian Soil Classification. The same comment may also apply to the SOILpak series available for other cropping industries (e.g. SOILpak for vegetable growers, SOILpak for the northern wheat belt).

7.4. Optimisation of the Data Entry Interface

The web page interface fulfils all requirements for entry of field data but could be improved to increase loading speed, efficiency and improve readability. The inflow and runoff hydrographs are one prime example. They consist of large number of automatically uploaded data elements which require considerable room on the page and are responsible for significant loading delays. A re-design of the page would include hiding such data and re-organising the important information to decrease the page size. It is envisaged that several areas for improvement will be identified when ISID is released to a wider audience of users, requiring some minor changes to the system. It is envisaged that the improved interface design would be implemented during this time.

7.5. Expansion to Other Industries

ISID has been developed for the Australian cotton industry and is therefore has been designed to represent the management practices (e.g. siphon type inflow) and irrigation districts where cotton is grown. Despite this, the database itself was designed to be generic and hence can be applied across any industry where furrow irrigation is practiced. Users can currently specify crops other than cotton using the "crop" drop-down in the "Season and Irrigation History" section but cannot add additional irrigation districts. The list of soil types was devised in an attempt to represent all Australian soils of agricultural importance but additional orders or sub-orders can be added with little effort. As a result, ISID is adaptable to any furrow-irrigated crop with minimal additional work.

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Appendix – ISID User Manual

ISID

Irrimate Surface Irrigation Database

User Manual and Technical Documentation

April 2008

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Toowoomba

NCEA Publication 1002691/1

Disclaimer

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Contents

1. Introduction

1.1. Overview

The Irrimate Surface Irrigation Database, known by the acronym ISID is designed to collate field measurements and simulation results to facilitate benchmarking of surface irrigation performance at the farm, catchment and industry levels.

The process of field evaluation has been greatly successful over the past decade. Considering Irrimate consultants alone there was in excess of 300 evaluations performed prior to and including the 2004-2005 season (Raine et. al. 2005). There is no doubt that the resulting changes to field management have been responsible for substantial improvements in water use efficiency across the Australian irrigation sector. However, the data recording and reporting processes have been managed with different levels of rigour, resulting in a large volume of information with little consistency between individuals or organisations. This makes it almost impossible to provide industry wide statistics benchmarking existing performance and demonstrating realised and potential improvements to irrigation performance. ISID was conceived in an attempt to standardise data recording procedures and to provide a secure database for collation of all the measurements required to benchmark irrigation performance.

ISID is fully compatible with the Irrimate™ system. It provides the ability to record and store all data necessary to conduct simulation runs, system evaluation and optimisation using Irrimate™ procedures. However, the system is generic and may be applied to a range of field measurement and evaluation techniques.

The NCEA has identified a number of areas for improvement and already has plans for the next generation of ISID. Any user comments or suggestions would be greatly appreciated.

This tool only facilitates measurements recorded from furrow irrigation evaluations. A similar tool, IPART (Irrigation Performance Audit and Reporting Tool) is available for pressurised irrigation systems including but not limited to travelling guns, solid set sprinklers, drip/micro sprinklers and centre pivot/lateral move irrigators. Those interested to gain access to IPART should contact the National Centre for Engineering in Agriculture.

NCEA
University of Southern Queensland
West Street
Toowoomba Qld, 4350

Ph: 07 4631 1817
Fax: 07 4631 1870
Email: ncea@usq.edu.au
www.ncea.org.au

2. Accessing ISID

2.1. The Web Interface

ISID can be accessed from any location through the World Wide Web using one of the popular web browsers. Currently ISID is located on the NCEA web server and can be found at:

http://139.86.208.170/isid

Currently all features of ISID are fully compatible with Microsoft Internet Explorer, Mozilla Firefox and Netscape Navigator. Users experiencing issues with alternative internet browsers should install one of the mentioned options.

Internet Explorer – Included within all versions of Microsoft Windows (e.g. XP, Vista).

Mozilla Firefox – A free (open source) browser developed by Mozilla, available from http://www.mozilla.com/en-US/

Netscape Navigator – The once popular but now unsupported web browser http://browser.netscape.com/

2.2. User Security

Access to ISID is controlled using a secure login system. A user is only granted access to the database after entering a valid username and password. ISID contains two different levels of access, the field technician/grower level and the overview or summary level.

A field technician/grower access allows the user to create new and edit existing evaluations. In addition, they are able to perform searches and statistical analysis across the evaluations they have entered. The users at this level do not have any access to the data entered by other users and cannot generate summaries based on the information from any other user.

The overview access level enables the user to perform analysis of all the data contained within the database entered by all users. ISID includes measures to maintain confidentiality during calculation of these statistics. At this level users are only permitted to view summary data calculated from a number of events. They have no access to data relating to the evaluations location and cannot interrogate the database to obtain input data or simulation results of a particular field or property. In some cases the combination of search options may enable an overview user to present the results of an individual property. ISID ensures confidentiality by hiding the summary statistics when any particular search returns less than a pre-set number of evaluations.

2.3. Further Assistance

An online, up to date version of this manual is available by clicking the ***Manual*** link on the menu found on the Homepage that follows the login page:

If you experience any difficulties in accessing the server or using ISID please send all enquires to:

Malcolm Gillies,
Cooperative Research Centre for Irrigation Futures (CRC IF),
National Centre for Engineering in Agriculture (NCEA),
University of Southern Queensland (USQ),
Toowoomba, QLD, 4350

Ph: 07 4631 1715
Email: gilliesm@usq.edu.au

or

NCEA
Ph: 07 4631 1817
Email: ncea@usq.edu.au

3. Guide to the ISID interface

3.1. Login Page

Loading the ISID web address will open the default login screen as shown in Figure 3.1. A valid username and password must be entered into the appropriate boxes before proceeding. Accounts cannot be created through the web interface; all potential users are requested to contact the system administrator in order to be assigned a new username and password. The username is typically comprised of the persons first and last names. Anyone experiencing problems logging in or those who have forgot passwords are urged to contact the NCEA using one of the email addresses listed above. After clicking ***Log In*** ISID loads the user homepage, the form of which is determined by the account type.

The Irrimate Surface Irrigation Database (ISID) is designed to assist in the evaluation and collation of data from the Irrimate infield system.

ISID was developed by the National Centre for Engineering in Agriculture at the University of Southern Queensland. This work was funded by the Cotton Catchment Communities CRC (CCC CRC) in collaboration with the Queensland Government through the Department of Primary Industries and Fisheries (QDPI&F).

Figure 3.1 – ISID welcome and login page

3.2. Login Issues

In some cases the browser configuration may prevent users from completing the login process. Successful login requires ISID to save cookies on the user’s computer, which is disabled under the highest security settings.

If having problems logging in, try the following:

1) Ensure that caps-lock is disabled.
2) Re-enter the username and password.
3) Click the ***Log In*** button.
4) Make note of whether the following message is displayed below the login boxes:

The username/password combination you gave was invalid. Please make sure that caps lock is off, and try again.

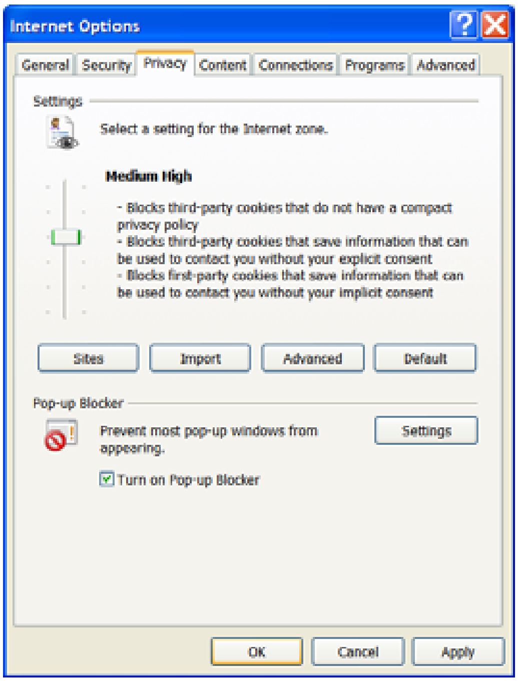
If the above message is displayed then either the password is incorrect or the entered username does not exist. If nothing appears to change (the above message is not displayed) this indicates that the password is correct but the browser has blocked the website, please follow the instructions below for your chosen browser:

3.2.1. Microsoft Internet Explorer

Internet Explorer displays an icon (Figure 3.2) in the status bar at the bottom of the browser window whenever a cookie is blocked. Cookies must be enabled in order to successfully log onto the system.

Figure 3.2 – Blocked cookie icon for Internet Explorer 7

To enable cookies in Internet Explorer, navigate to ***Internet options*** from the ***Tools*** menu. Click on the ***Privacy*** tab and change the security level to “*medium high*” or “*medium*”.



Select a setting for the Internet zone.

Medium High

- Blocks third-party cookies that do not have a compact privacy policy
- Blocks third-party cookies that save information that can be used to contact you without your explicit consent
- Blocks first-party cookies that save information that can be used to contact you without your implicit consent

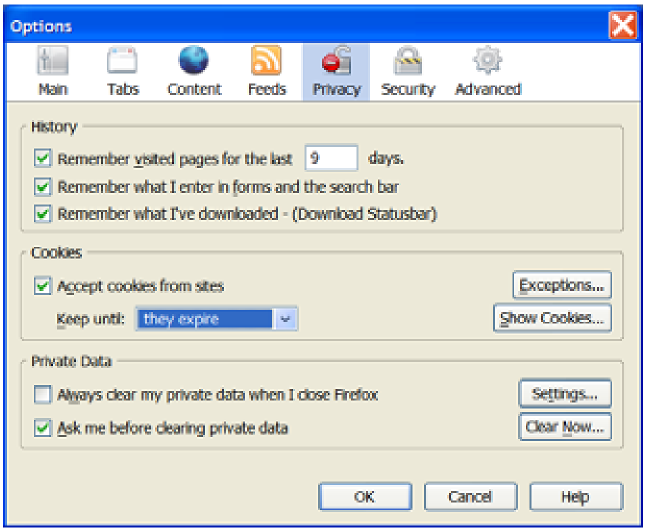
Prevent most pop-up windows from appearing.

☑ Turn on Pop-up Blocker

Figure 3.3 – Changing security settings in Internet explorer 7.

3.2.2. *Mozilla Firefox*

Mozilla Firefox behaves in a similar manner to internet explorer in relation to internet security settings. However, there is no visible indication (no icon) that the site has been blocked. To enable cookies within Firefox navigate to the ***Tools*** menu and select ***Options***. On the dialog, click the ***Privacy*** icon and ensure that "*Accept cookies from sites*" is enabled. Click ***OK*** and then reload the page



History

☑ Remember visited pages for the last 9 days.

☑ Remember what I enter in forms and the search bar

☑ Remember what I've downloaded - (Download Statusbar)

Cookies

☑ Accept cookies from sites

Keep until: they expire

Private Data

☐ Always clear my private data when I close Firefox

☑ Ask me before clearing private data

Figure 3.4 – Altering the security settings in Mozilla Firefox 2.0.

3.3. Overview User Level

The homepage of the overview user, accessed using an overview level username should look similar to Figure 6.1. Features available to the overview user are discussed in detail later in section 6.2.

3.4. Field Technician/Grower Level

After logging in with a field technician/grower username the user is presented with a homepage that should look something like Figure 3.5. Initially the page will be blank but later will contain links to all evaluations previously entered by that user.

The ***Search by*** section enables the user to filter the evaluations shown on the page by selecting any number of search criteria. This is particularly useful in those cases where the account contains a large number of evaluations. The check box titled ***Include summary statistics*** presents a summary of the results calculated across the evaluations entered by the user and satisfying the specified search criteria (see section 6).

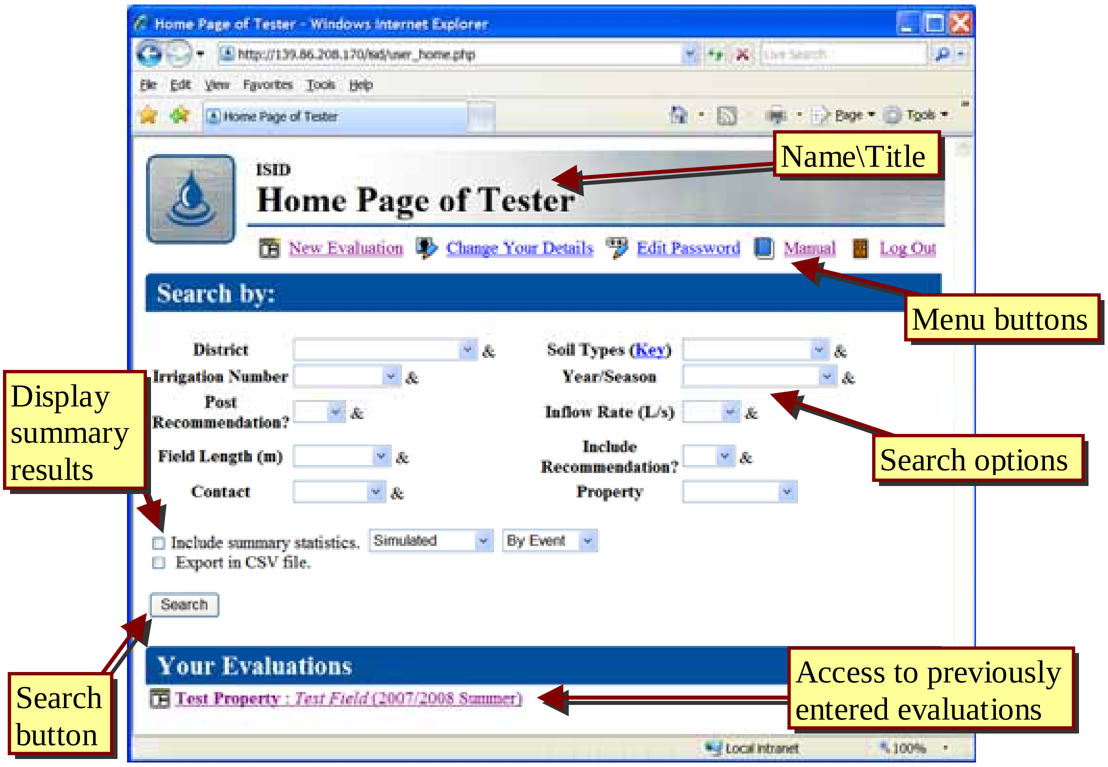
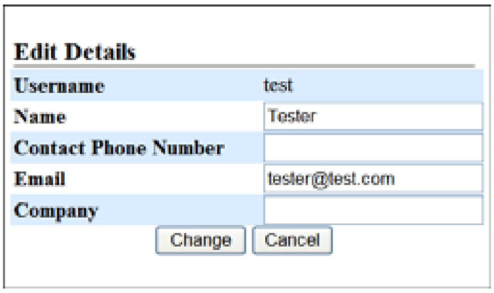


Figure 3.5 – ISID field technician homepage

3.5. Account Management

The ***Change Your Details*** link found on the menu opens a popup window as shown in Figure 3.6 prompting the user to provide contact details and change the login password. Users are provided with a password by the administrator on initiation of a new account. For security sake it is recommended that users change the password on first login. Before making any changes remember that the password is case sensitive. The ***Username*** cannot be changed, the ***Name*** field relates to the name inserted on the top banner as seen in Figure 3.5 (i.e. Tester). The contact details provided here aid in administration of the ISID system, All users can be easily contacted in the event of any problems with the database.


Edit Details

Username	test
Name	Tester
Contact Phone Number	
Email	tester@test.com
Company	

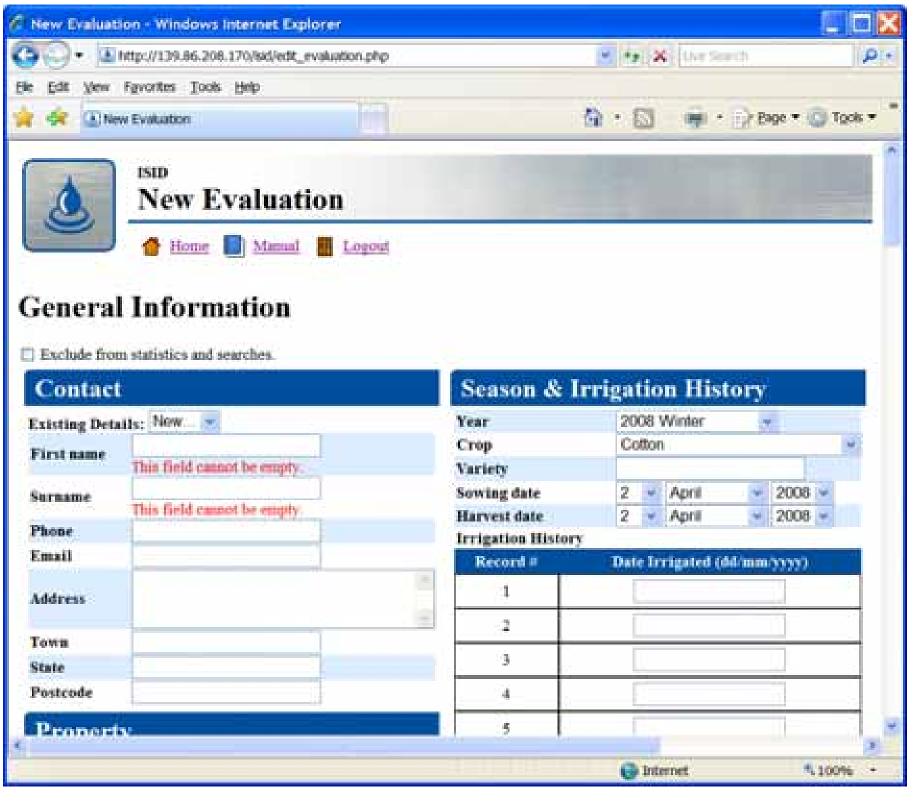
Figure 3.6 – Changing user details

4. Creating and Editing Evaluations

4.1. Adding New Evaluations

This section relates to the data entry process the users must follow when creating and/or editing an existing evaluation and as such has little relevance to the overview user.

The first step is to click the ***New Evaluation*** button:
ISID then loads a blank evaluation as shown in Figure 4.1.



ISID
New Evaluation

General Information

☐ Exclude from statistics and searches.

Contact

Existing Details: New...
First name
This field cannot be empty.
Surname
This field cannot be empty.
Phone
Email
Address
Town
State
Postcode

Property

Season & Irrigation History

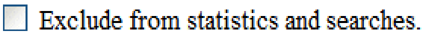
Year: 2008 Winter
Crop: Cotton
Variety
Sowing date: 2 April 2008
Harvest date: 2 April 2008

Irrigation History

Record #	Date Irrigated (dd/mm/yyyy)
1	
2	
3	
4	
5	

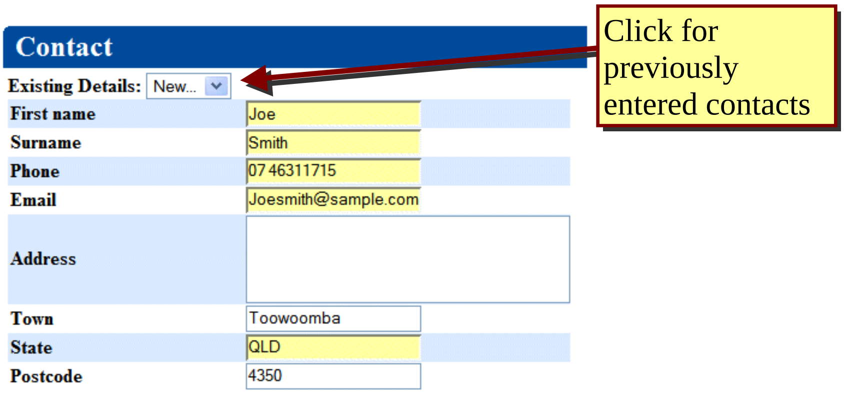
Figure 4.1 – New evaluation

The ***Exclude from statistics and searches*** checkbox, located at the top of the evaluation page enables the user to enter data into the database but hide the results from any summary statistics generated by an overview user. This is particularly useful where there is doubt in the validity of the results; it permits removal of an evaluation from the ISID database without actually removing the evaluation from the users account. This option may be used to hide those evaluations that are half completed or hide the "test evaluations" created whilst learning how to use the ISID interface. All "excluded" evaluations may be added to the database at any later time by de-selecting this option whilst editing in editing mode.


☐ Exclude from statistics and searches.

4.2. Contact

The first section of the edit evaluation screen stores the contact details (Figure 4.2) of the grower or property manager (not the person entering the information). These details are not used in generation of the summary statistics. However, users are advised to complete as many boxes as possible to aid in identification.



Click for previously entered contacts

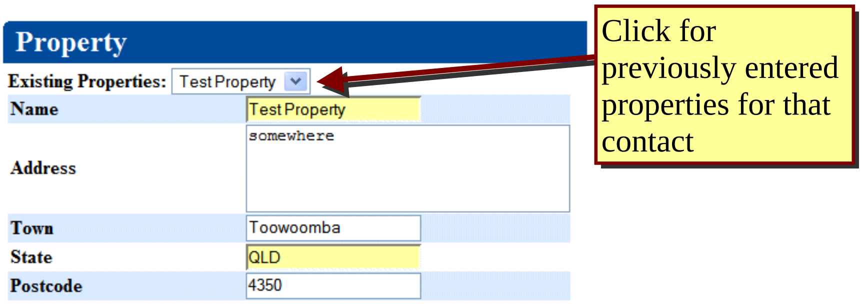
Existing Details:	New...
First name	Joe
Surname	Smith
Phone	07 46311715
Email	Joesmith@sample.com
Address	
Town	Toowoomba
State	QLD
Postcode	4350

Figure 4.2 – Contact information

Both the ***First name*** and ***Surname*** boxes must contain valid characters, when they are empty the message ***This field cannot be empty*** will be displayed as can be seen in Figure 4.1. In those cases where the name is not known enter something like “Unknown” or “Anon”. The drop-down box next to ***Existing Details*** displays a list of all the previously entered contact details, select the appropriate name and all details will be filled in automatically.

4.3. Property

The property information, shown in Figure 4.3 identifies the name and location of the property. As for the contact details, the ***Name*** input cannot be blank. ***Existing Properties*** behaves similarly to the drop-down box for the Contact information.



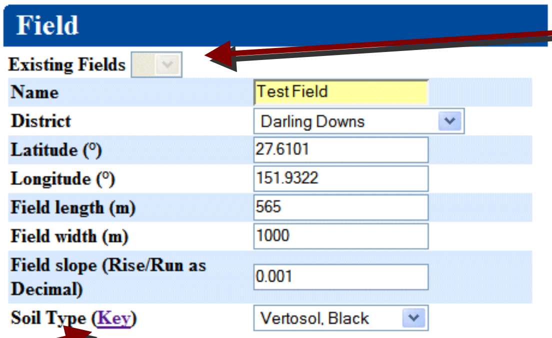
Click for previously entered properties for that contact

Existing Properties:	Test Property
Name	Test Property
Address	somewhere
Town	Toowoomba
State	QLD
Postcode	4350

Figure 4.3 – Property information

4.4. Field

The field information (Figure 4.4) describes the location and characteristics of the field. With the exception of the latitude, longitude and field width it is very important that all information in this section is completed. Unlike the ***Contact*** or ***Property*** information the field information is essential to the generation of summary statistics, particularly the ***District*** and ***Soil Type*** fields. The field ***Name*** is crucial since it is used to identify the evaluation if the user wishes to access the data in the future. ***Existing Fields*** behaves in a similar manner as the drop-down box for the Contact information.



Existing Fields	
Name	Test Field
District	Darling Downs
Latitude (°)	27.6101
Longitude (°)	151.9322
Field length (m)	565
Field width (m)	1000
Field slope (Rise/Run as Decimal)	0.001
Soil Type (Key)	Vertosol, Black

Click for previously entered fields for that property

Quick guide to Soil Type Key

Figure 4.4 – Field information

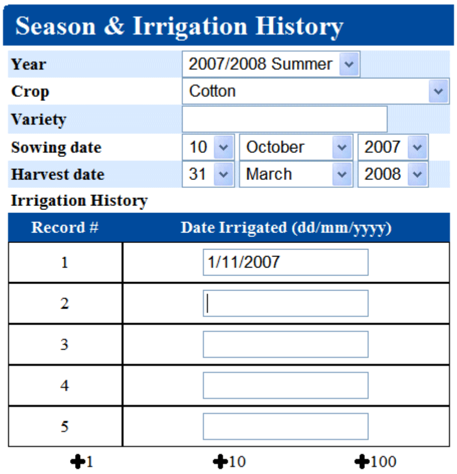
The ***District*** input is entered via a drop down box containing a list of districts or catchments where cotton is grown. Users must select one option, there is no facility to enter a new or unknown district. If a field is encountered in some region outside those specified the user should contact the administrator. The ***Field length*** and ***Field slope*** in this section are provided for descriptive purposes, each furrow within the evaluation contains individual values for these inputs.

The ***Soil Type*** is very important as it serves as a primary search filter within ISID. To correctly identify a soil profile users should consult the Soil Key (accessed by clicking ***Key*** next to Soil Type) combined with the information provided later in Section 7 of this manual.

4.5. Season and Irrigation History

The season and irrigation history section contains information describing the season and crop growth. It is imperative that the user supplies the correct information for the ***Year*** and ***Crop***. The ***Variety***, ***Sowing date*** and ***Harvest date*** fields are less important.

Irrigation history provides space to record the dates of the irrigations throughout the season. The values entered here do not reference the ***Event*** information in any way. The table is provided to enable users to enter the dates of all irrigation events and is not restricted to those irrigations with corresponding evaluations.



Season & Irrigation History

Year: 2007/2008 Summer
Crop: Cotton
Variety:
Sowing date: 10 October 2007
Harvest date: 31 March 2008

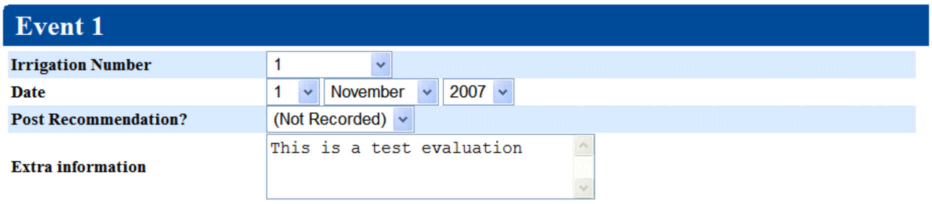
Irrigation History

Record #	Date Irrigated (dd/mm/yyyy)
1	1/11/2007
2	
3	
4	
5	

Figure 4.5 – Season and irrigation history information

4.6. Event

The event section provides the general details of a particular irrigation event. Note that each “Evaluation” can contain multiple (up to 20) events. The ***Irrigation Number*** refers to event count of the current irrigation with irrigation number 1 being the first “in season” irrigation. Irrigations prior to planting are classed as “*Preirrigation*”. The irrigation ***Date*** corresponds to the date that the irrigation occurred, NOT the date the data was downloaded or analysed. ISID does not allow more than one event to have the same irrigation number, multiple measurements collected during a single event must be entered as furrows underneath a single event.



Event 1

Irrigation Number: 1
Date: 1 November 2007
Post Recommendation?: (Not Recorded)
Extra information: This is a test evaluation

Figure 4.6 – Event information

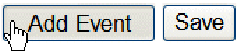
Post Recommendation prompts the user to record the status of the evaluation, i.e. either an evaluation performed on a field that has been managed according to a previous Irrimate analysis or a field that is managed according to the irrigator’s normal practice:

YES – means that the field is being managed following a previous optimisation.
NO – means that the field is NOT managed according to a previous optimisation.
(Not Recorded) – is provided for those irrigations where the evaluation history is not known.

Extra information provides a room for the user to enter a description of the irrigation or comments on the data. There is no standard format for this input field.

Adding New Events

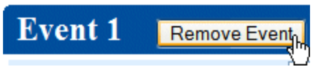
By default each evaluation possesses a single event, additional events can be added using the Add event button located at the bottom of the page:



When pressed, ISID will add a new evaluation to the end of the evaluation containing 1 measured furrow.

Removing Events

Individual events may be removed from the evaluation by clicking the Remove Event button located at the top of each event:

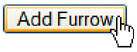


4.7. Furrow

Each event contains one furrow by default but any number of additional furrows can be added. Each furrow has unique values of field geometry, input data, water use, simulated results and recommended results. The input data is divided into several sections; the field measurements and associated advance, inflow and runoff data; estimated infiltration; simulation results and recommended results.

Adding New Furrows

New furrows can be added to any event at any time by clicking the ***Add Furrow*** button located at the end of that event:



Uploading Information

ISID contains a large number of data fields, the manual entry of which is a tedious process. Instead ISID provides a facility to load the majority of the required data from Infilt, IPARM and SIRMOD files. For further details on the upload procedure and how to produce the necessary files see section 5.

Important: Although ISID provides the ability to load both Infilt and IPARM files you should only load one or the other.
E.g. select either 1 Infilt + 1 SIRMOD file or 1 IPARM + 1 SIRMOD file.

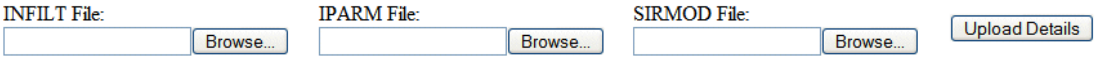


Figure 4.7 – Uploading Infilt, IPARM and SIRMOD files

4.7.1. Field Measurement Section

Found at the top left corner of each furrow the field measurement section (shown in Figure 4.9) contains the data describing the field measurements. The majority of these input fields are completed by uploading the Infilt/IPARM and SIRMOD files as described in section 5. Most data inputs are self explanatory for those users familiar with the Irrimate system.

- In most cases a single slope is sufficient to characterise the field geometry (i.e. using Slope 1 and Slope 1 Distance). Slope 2 and Slope 3 follow the same convention as used in SIRMOD (Figure 4.8) allowing the slope to change twice along the length of the furrow.

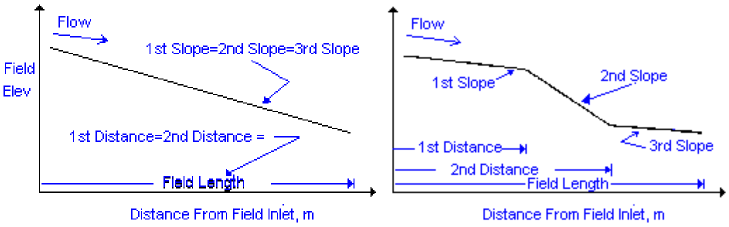
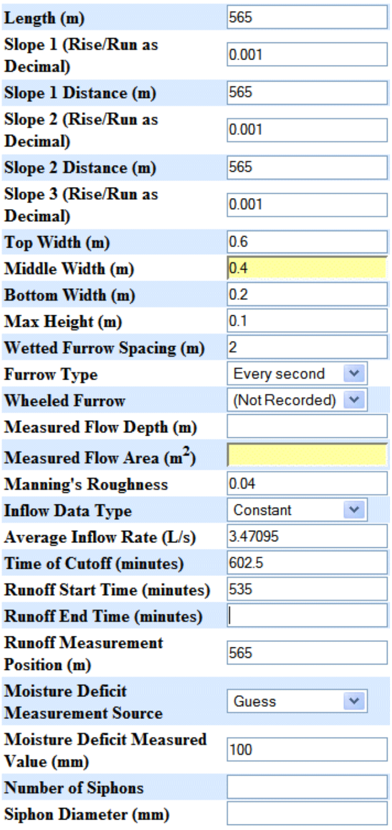


Figure 4.8 – Naming convention for slope as used in SIRMOD

- The furrow dimensions i.e. ***Top***, ***Middle*** and ***Bottom*** widths and ***Max Height*** refer to the dimensions of the entire furrow NOT just the portion submerged.
- ***Furrow Type*** provides four options, not recorded, every furrow, every second (common e.g. 1 m spacing with alternate furrow irrigated) or bed (where the wetted furrows are separated by a wide bed).
- ***Measured Flow Depth/Area*** contains the measured upstream condition used in Infilt or IPARM.
- ***Manning's Roughness*** is the roughness parameter used in IPARM (different to the SIRMOD value).
- ***Inflow Data Type*** describes the nature of the inflow hydrograph. The inflow rate may be either constant or variable with time.
- ***Average Inflow Rate*** is the time-averaged inflow rate used in both estimation of the infiltration parameters and SIRMOD simuation.
- ***Time of Cutoff*** is the duration of inflow.
- ***Runoff measurement Position*** is the distance of the measurement flume from the upstream end of the field.
- ***Moisture Deficit Meas. Source*** stores the source of the deficit data and hence quality of the estimation.
- ***Moisture Deficit Meas. Value*** is the desired depth of application, all infiltration in excess of this value is deep drainage
- ***Number of Siphons and Siphon Diameter*** store the siphon characteristics, leave blank if unknown.

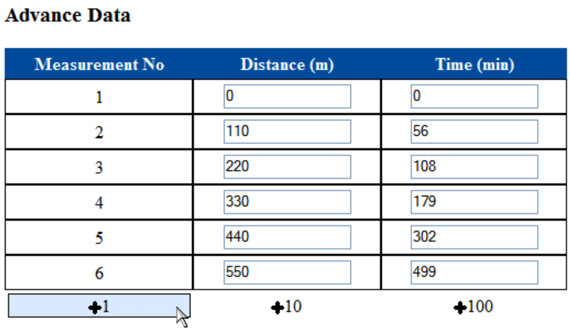


Length (m)	565
Slope 1 (Rise/Run as Decimal)	0.001
Slope 1 Distance (m)	565
Slope 2 (Rise/Run as Decimal)	0.001
Slope 2 Distance (m)	565
Slope 3 (Rise/Run as Decimal)	0.001
Top Width (m)	0.6
Middle Width (m)	0.4
Bottom Width (m)	0.2
Max Height (m)	0.1
Wetted Furrow Spacing (m)	2
Furrow Type	Every second
Wheeled Furrow	(Not Recorded)
Measured Flow Depth (m)	
Measured Flow Area (m^2)	
Manning's Roughness	0.04
Inflow Data Type	Constant
Average Inflow Rate (L/s)	3.47095
Time of Cutoff (minutes)	602.5
Runoff Start Time (minutes)	535
Runoff End Time (minutes)	
Runoff Measurement Position (m)	565
Moisture Deficit Measurement Source	Guess
Moisture Deficit Measured Value (mm)	100
Number of Siphons	
Siphon Diameter (mm)	

Figure 4.9 – Field measurements section

Advance Data

The advance data (Figure 4.10) can be found on the upper right side of each furrow section. The advance points are presented in tabular format with provision for any number of data points. Additional row(s) are added by pressing one of the three buttons on the bottom of the table. The advance points are entered in ascending order staring from the upstream end of the furrow. Most users will have no need to edit the table manually as the data is automatically uploaded from both the Infilt or IPARM files.



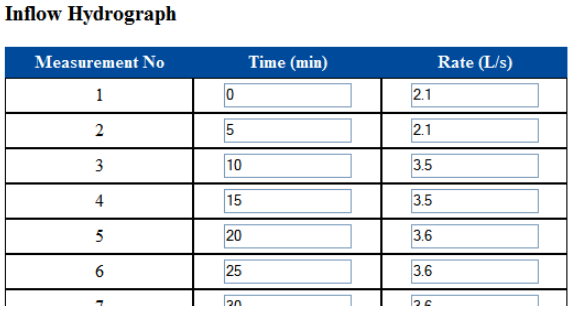
Advance Data

Measurement No	Distance (m)	Time (min)
1	0	0
2	110	56
3	220	108
4	330	179
5	440	302
6	550	499

Figure 4.10 – Advance data

Inflow and Runoff Hydrograph

The inflow and runoff hydrographs are located underneath the advance data on the right hand side of the browser window. Similarly to the advance data, these tables are automatically populated using the uploaded IPARM (not Infilt) file.



Inflow Hydrograph

Measurement No	Time (min)	Rate (L/s)
1	0	2.1
2	5	2.1
3	10	3.5
4	15	3.5
5	20	3.6
6	25	3.6
7	30	3.6

Figure 4.11 – Inflow Data

The data contained within these tables is not used during the calculation of simulation results or summary statistics. As such it is pointless to manually enter the values in those cases where they are not contained within the IPARM file. They are included for future versions of ISID that will include built-in capacity for online parameter estimation and/or simulation.

4.7.2. Infiltration Estimation

For furrow irrigation, the soil intake (infiltration) rate is commonly described using the Modified Kostiakov equation:

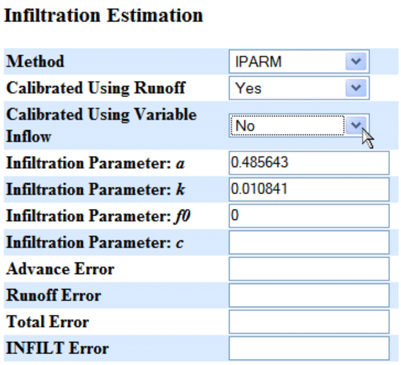
$$Z = k\tau^{a} + f_{0}\tau + C^{*}$$

where Z is the cumulative infiltration (volume infiltrated (m^3) per metre length of furrow) and τ is the opportunity or ponding time (minutes). The three "infiltration parameters"; a, k, and f_0 are empirical constants that must be estimated.

C, the "cracking" term is usually ignored and hence set to equal zero. In almost all cases the three parameter infiltration equation is sufficient for describing the behaviour of cracking soils such as Vertosols. The parameter is included within ISID for those rare instances where it is used; C is also used by SIRMOD but is usually set to zero.

Infiltration parameters differ significantly between fields, between irrigations and even between adjacent furrows in the same irrigation. In reality, infiltration rates also change along the furrow length. However, it is almost impossible to quantify this variability using normal Irrimate measurements. Infiltration parameters may be measured directly but are most commonly estimated indirectly from field measurements. For furrow irrigation the parameters may be estimated using the Infilt or IPARM models or perhaps the Two-point method. Infilt and IPARM require measurements of furrow characteristics, inflow rate and advance rate. IPARM differs in that it can also accommodate runoff (to improve the fit at greater opportunity times) and variable inflow data (Infilt assumes that inflow rates are constant). The resulting values of a, k and f_0 are used to calibrate the simulation model SIRMOD.

The infiltration estimation section within ISID (Figure 4.12) contains data fields for the three standard infiltration parameters (a, k and f_0) and the cracking term (C). The values of a, k, f_0 and C are automatically uploaded from the SIRMOD input file using the button shown in Figure 4.7.



Infiltration Estimation

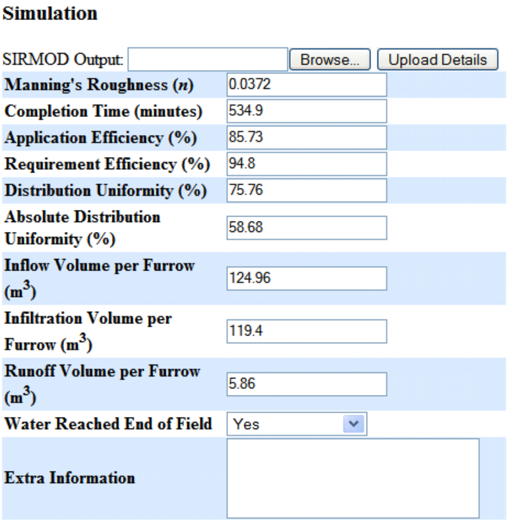
Method	IPARM
Calibrated Using Runoff	Yes
Calibrated Using Variable Inflow	No
Infiltration Parameter: *a*	0.485643
Infiltration Parameter: *k*	0.010841
Infiltration Parameter: *f0*	0
Infiltration Parameter: *c*	
Advance Error	
Runoff Error	
Total Error	
INFILT Error	

Figure 4.12 – Infiltration estimation section

The first three boxes describe the method used to estimate the parameters. This information is not crucial to the ISID summary results but aids in determination of the method used. Note that the infiltration parameters will always differ, sometimes substantially depending on the approach used to estimate them.

4.7.3. Simulation

The simulation section (Figure 4.13) contains all the data required to describe the irrigation performance. All data required for this section can be loaded from the SIRMOD output file (*.out), see section 5.3 for instructions. The ***Water Reached End of Field*** dropdown is used to correct the minimum depth applied in those situations where the water does not reach the end of the field. An answer “*NO*” indicates that the inflow is cut off early and the advancing front never reaches the end of the field and hence the minimum applied depth is equal to 0.0 mm. ***Extra Information*** provides space for comments on the field measurements or simulation results. The extra info can be valuable providing descriptive information for future reference.



Simulation

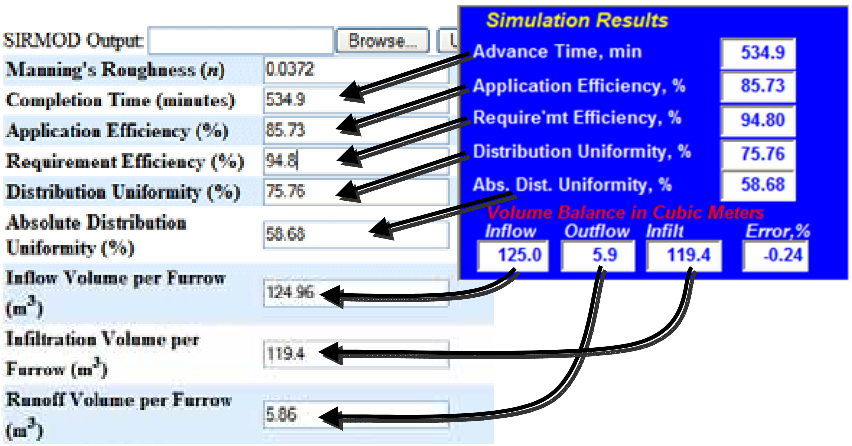
SIRMOD Output: [Browse...] [Upload Details]

Manning's Roughness (*n*)	0.0372
Completion Time (minutes)	534.9
Application Efficiency (%)	85.73
Requirement Efficiency (%)	94.8
Distribution Uniformity (%)	75.76
Absolute Distribution Uniformity (%)	58.68
Inflow Volume per Furrow (m^3)	124.96
Infiltration Volume per Furrow (m^3)	119.4
Runoff Volume per Furrow (m^3)	5.86
Water Reached End of Field	Yes
Extra Information	

Figure 4.13 – Simulation results section

Warning: Always check the *Water Reached End of Field* input after loading a SIRMOD output file, in some cases the user might be required to correct both this and the *Completion Time*.

Alternatively, the simulation results may be transferred manually from the SIRMOD main as shown in Figure 4.14. All data fields in this section have the same units as used in SIRMOD. Just ensure that the user preferences are set to metric by selecting the ***Metric*** option from the ***File->Units*** menu in SIRMOD.



SIRMOD Output: [Browse...]

Manning's Roughness (*n*)	0.0372
Completion Time (minutes)	534.9
Application Efficiency (%)	85.73
Requirement Efficiency (%)	94.8
Distribution Uniformity (%)	75.76
Absolute Distribution Uniformity (%)	58.68
Inflow Volume per Furrow (m^3)	124.96
Infiltration Volume per Furrow (m^3)	119.4
Runoff Volume per Furrow (m^3)	5.86

Simulation Results

Advance Time, min	534.9
Application Efficiency, %	85.73
Require'mt Efficiency, %	94.80
Distribution Uniformity, %	75.76
Abs. Dist. Uniformity, %	58.68

Volume Balance in Cubic Meters

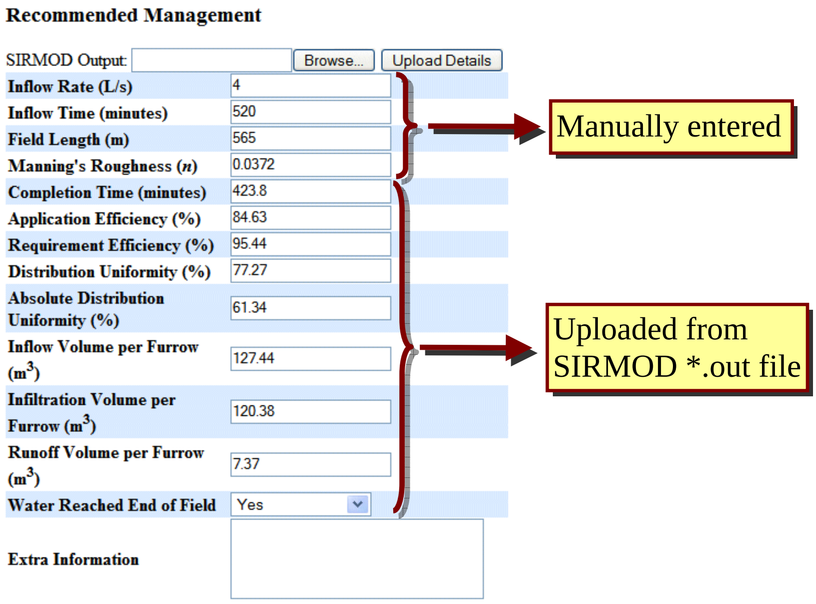
Inflow	*Outflow*	*Infilt*	*Error,%*
125.0	5.9	119.4	-0.24

Figure 4.14 – Transferring simulation results from SIRMOD

Values such as the minimum infiltrated depth, average infiltrated depth and averaged applied depths are estimated using combinations of the data entered in this section and select items from the field measurements section.

4.7.4. Recommended Management

The recommended management section (Figure 4.15) provides the ability to capture the performance of a single "optimised" field management. In most cases, the final stage of field analysis involves some type of optimisation where the user investigates several potential options to alter field management in order to achieve a desired outcome, typically a reduction in water use and/or an increase in uniformity.



Recommended Management

SIRMOD Output:

Inflow Rate (L/s)	4
Inflow Time (minutes)	520
Field Length (m)	565
Manning's Roughness (*n*)	0.0372
Completion Time (minutes)	423.8
Application Efficiency (%)	84.63
Requirement Efficiency (%)	95.44
Distribution Uniformity (%)	77.27
Absolute Distribution Uniformity (%)	61.34
Inflow Volume per Furrow (m^3)	127.44
Infiltration Volume per Furrow (m^3)	120.38
Runoff Volume per Furrow (m^3)	7.37
Water Reached End of Field	Yes
Extra Information	

Manually entered

Uploaded from SIRMOD *.out file

Figure 4.15 – Recommended management section

The last 7 numerical inputs (application, requirement efficiency, distribution and absolute distribution uniformities and inflow, infiltration and runoff volume) can be uploaded from the SIRMOD output file. The ***Inflow Rate***, ***Inflow Time***, ***Field Length***, ***Manning's Roughness*** must be entered manually by the user.

4.8. Editing Existing Evaluations

From the homepage, the user may view existing evaluations by clicking the links in the ***Your Evaluations*** section. On doing so, ISID will load the evaluation in read-only "report" mode, all data is displayed but cannot be altered by the user. The only other difference between the read-only "report" mode evaluation page and the edible evaluation page is the inclusion of the calculated values for minimum and average infiltrated depths and applied and deep drainage depths. These can be found immediately following the ***Extra Information*** in each simulation section.

To edit the current evaluation click the ***Edit*** link in the menu: Edit

ISID will now reload the page in editable mode, now the user may alter all parts of the evaluation, including adding and removing events and furrows.

4.9. Saving Entered Data

Any time that new data is entered or changed within the new/edit evaluation page the user must press the ***Save*** button, which is located at the bottom of the screen. ISID will not store or change anything in the database without using the save procedure. All changes made to the data on screen will be lost if the current evaluation is closed. When entering multiple furrows/events for the same event it is recommended that users save changes regularly to avoid loosing their work.

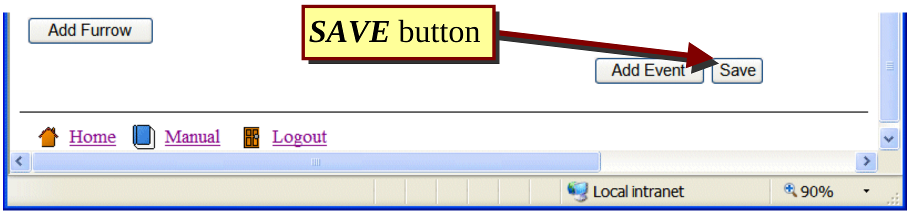
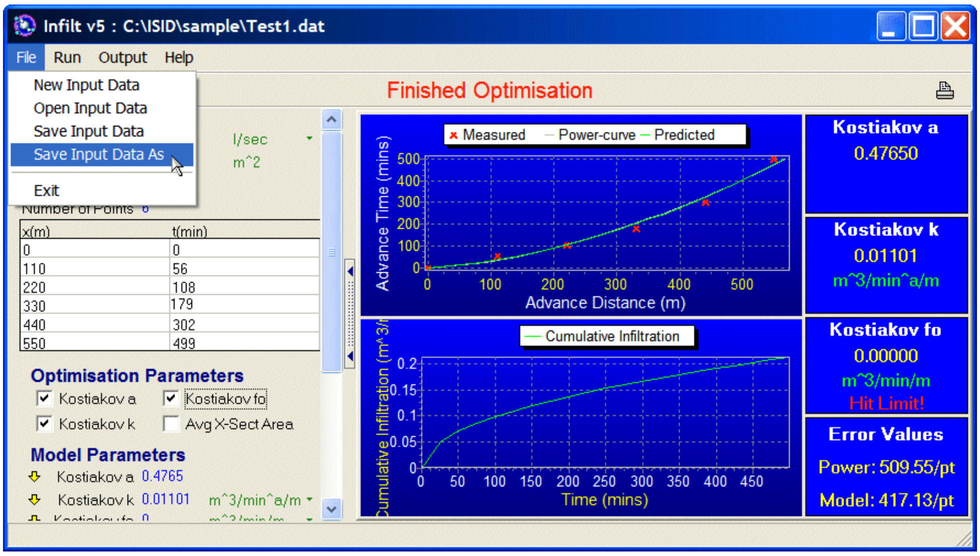


Figure 4.16 – Locating the Save button

5. Uploading InfiltV5, IPARM and SIRMOD files

ISID requests a large quantity data for each furrow in the evaluation. Manual entry of such values is a time consuming process which is subject to a fair level of data entry error. The vast majority of data contained in ISID is already required by the Irrimate software packages Infilt, IPARM and SIRMOD and is hence stored in the input files. The upload functionality of ISID was developed to take advantage of this thereby speeding up the data entry process.

5.1. Infilt files



Number of Points 6

x(m)	t(min)
0	0
110	56
220	108
330	179
440	302
550	499

Optimisation Parameters

☑ Kostiakov a ☑ Kostiakov fo

☑ Kostiakov k ☐ Avg X-Sect Area

Model Parameters

Kostiakov a 0.4765

Kostiakov k 0.01101 m^3/min^a/m

Kostiakov fo 0 m^3/min/m

Kostiakov a
0.47650

Kostiakov k
0.01101
m^3/min^a/m

Kostiakov fo
0.00000
m^3/min/m
Hit Limit!

Error Values
Power: 509.55/pt
Model: 417.13/pt

Figure 5.1 – Infilt V5

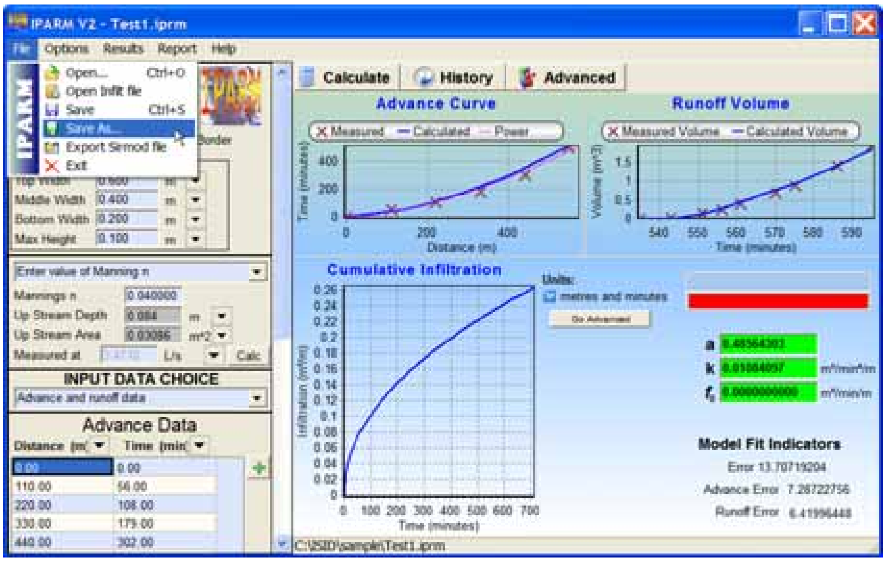
InfiltV5 (Figure 5.1) is a software package designed to estimate the parameters of the Modified Kostiakov infiltration equation from measurements of inflow rate, and water front advance data. Saving a input file within InfiltV5 writes all input data to a ASCII text file with the extension ***.dat**. Users need not concern themselves with the contents of the file other than knowing that it can be used to populate the database. ISID does not have any requirements on the filename or path. For future reference it is best to save the Infilt file using a name that adequately describes the field, event and furrow.

When the **Infilt** data file is uploaded into ISID it will load the values of:

- Measured flow area (m^2)
- Average inflow rate (L/s)
- Advance data, filling the advance data table (e.g. Figure 4.10)

5.2. IPARM files

IPARM (Figure 5.2) is similar to InfiltV5 in that it serves as a tool to estimate the infiltration characteristic from field measurements. Both apply an inverse solution of the simplistic (when compared to SIRMOD) volume balance model. The major differences between the two are (a) the ability to use runoff data and (b) the use of the full inflow hydrograph in cases of variable inflow. As such, the input files for IPARM contain far more information useful for populating the ISID database. Selecting “***Save***” or “***Save As***” from the file menu of IPARM will create an input file with extension ***.iprm**.



Top Width 0.600 m
Middle Width 0.400 m
Bottom Width 0.200 m
Max Height 0.100 m

Enter value of Manning n

Mannings n 0.040000
Up Stream Depth 0.084 m
Up Stream Area 0.03086 m^2
Measured at L/s

INPUT DATA CHOICE: Advance and runoff data

Advance Data

Distance (m)	Time (min)
0.00	0.00
110.00	56.00
220.00	108.00
330.00	179.00
440.00	302.00

Units: ☑ metres and minutes

a 0.48564303
k 0.01084057 m³/min^a/m
f_0 0.0000000000 m³/min/m

Model Fit Indicators
Error 13.70719204
Advance Error 7.28722756
Runoff Error 6.41996448

C:\ISID\sample\Test1.iprm

Figure 5.2 – IPARM V2

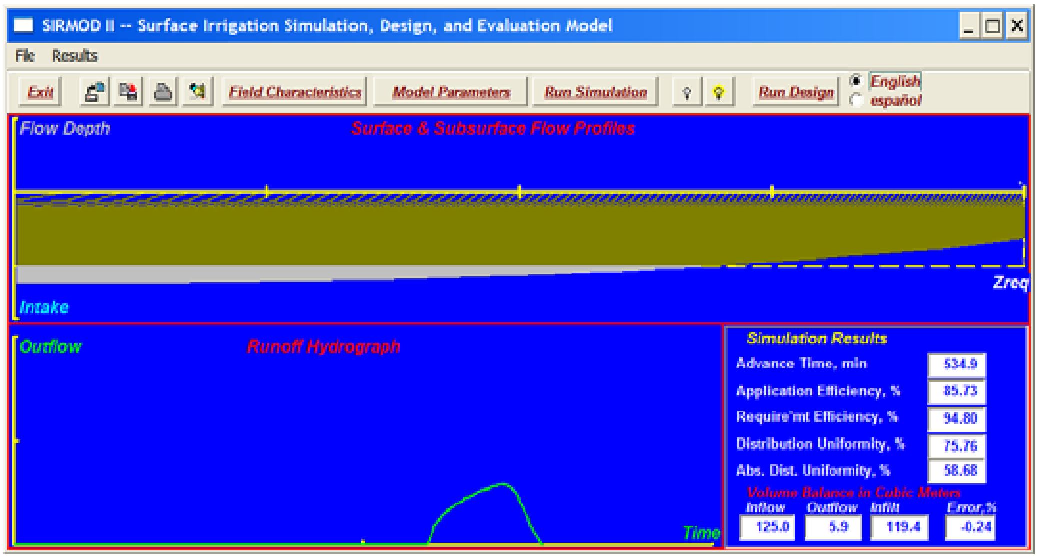
When the **IPARM** data file is uploaded into ISID it will load the values of:

- Field length (m)
- Slope
- Furrow dimensions – top width, middle width, bottom width and max height (m)
- Manning’s roughness
- Average inflow rate (L/s)

- Runoff start time (min) (if present in the file)
- Advance data, filling the advance data table (e.g. Figure 4.10).
- Inflow rates (if available), filling the inflow hydrograph table (e.g. Figure 4.11)
- Runoff rates (if available), filling the runoff hydrograph table

5.3. SIRMOD II input files

SIRMOD II is the standard software package for simulation and evaluation of surface irrigation under Irrimate™. SIRMOD (Walker 2003), applies the full hydrodynamic Saint-Venant equations to simulate the flow of water along a single furrow. The model computes numerous indicators of irrigation performance such as the efficiency and uniformity. The instructions in this manual refer to version II but apply equally to SIRMOD II. At the present time ISID cannot load input or output files from version III.



Simulation Results

Advance Time, min: 534.9
Application Efficiency, %: 85.73
Require'mt Efficiency, %: 94.80
Distribution Uniformity, %: 75.76
Abs. Dist. Uniformity, %: 58.68

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
125.0	5.9	119.4	-0.24

Figure 5.3 – SIRMOD II

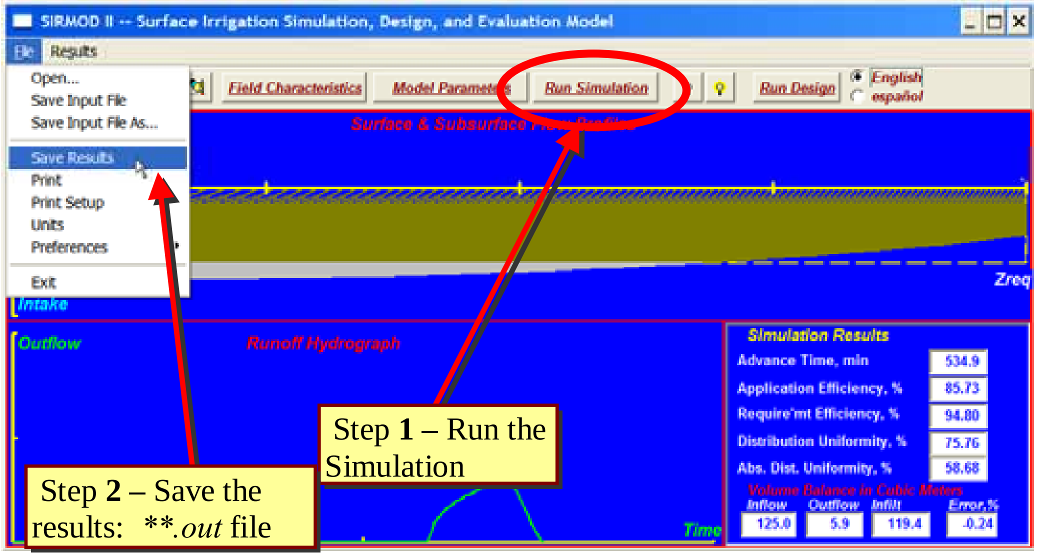
SIRMOD input files are created by selecting ***Save Input File*** or ***Save Input File As*** from the ***File*** menu, the files are saved with the *.cfg extension. SIRMOD II can have difficulties with long file names/paths as it is restricted to a total of 256 characters in the file path+name. Users must take this into account when selecting the location for file storage.

Uploading the **SIRMOD input** file data will load values of:

- Field Length (m)
- Slope (slope 1, slope 1 distance, slope 2, slope 2 distance and slope 3)
- Furrow dimensions – top width, middle width, bottom width and max height (m)
- Wetted furrow spacing (m)
- Average inflow rate (L/s)
- Time of cutoff (min)
- Moisture deficit (mm)
- Infiltration function – values for the infiltration parameters a, k and f_0
- Manning's roughness (for the simulation results section)

5.4. SIRMOD output files

SIRMOD output files contain the simulation results including the efficiency, uniformity and volumes of infiltration and runoff. Output files are generated by clicking ***Save Results*** from the ***File*** menu. The results of the most recently run simulation will be written to the specified file hence it is necessary to run the simulation with the current file and field settings before saving.



Simulation Results

Advance Time, min 534.9
Application Efficiency, % 85.73
Require'mt Efficiency, % 94.80
Distribution Uniformity, % 75.76
Abs. Dist. Uniformity, % 58.68

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
125.0	5.9	119.4	-0.24

Step **1** – Run the Simulation

Step **2** – Save the results: ***.out* file

Figure 5.4 – Producing the SIRMOD output file

When ISID uploads a **SIRMOD output** file it will load values of:

- Completion (of advance) time (minutes)
- Application efficiency (%)
- Requirement efficiency (%)
- Distribution uniformity (%)
- Absolute distribution uniformity (%)
- Inflow volume per furrow (m^3)
- Infiltration volume per furrow (m^3)
- Runoff volume per furrow (m^3)

5.5. Uploading Files

The data files are uploaded by clicking the ***Browse*** button located next to the desired file type:

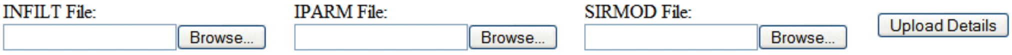
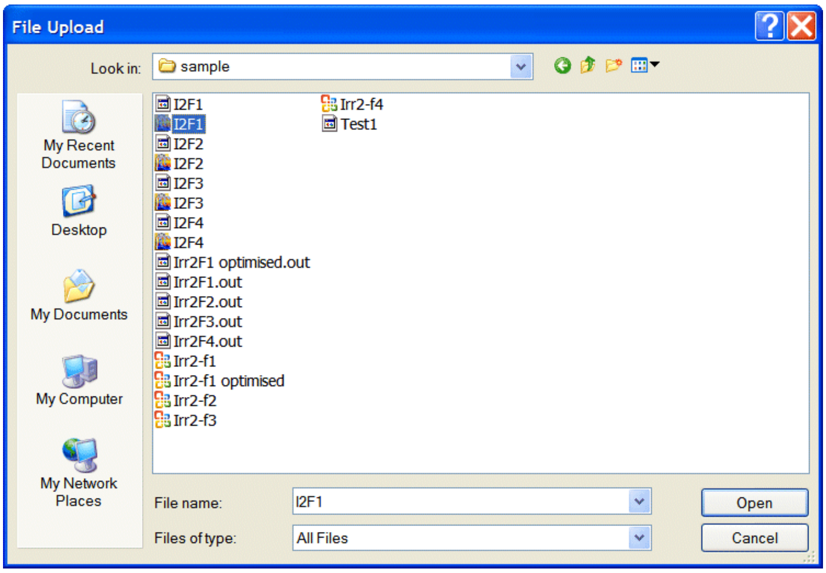


Figure 5.5 – Upload input file section

The ***File Upload*** window should look something like Figure 5.6, prompting the user to select the appropriate input file. In the example, Windows Explorer is hiding the file extensions for known types, making it difficult to correctly identify the different files.

Depending on the Windows settings these extensions may be visible to the user (see the hint below).



Look in: sample

File name: I2F1

Files of type: All Files

Figure 5.6 – Upload file window

Hint: If you are having difficulty distinguishing between the files you may alter the windows settings to display all file extensions. Open any folder, then select ***Tools->Folder Options*** *from the main menu, select the* **View** *tab and uncheck the "****Hide extensions for known file types****"* option.

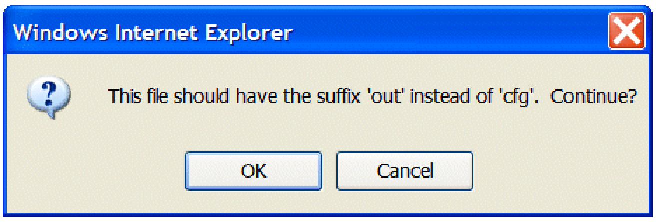
**** InfiltV5 files (*.dat)** may appear with a range of icons depending on other software installed on the computer. In the example in Figure 5.6 they are shown with:

** For systems where IPARM V2 is installed, **IPARM input files (*.iprm)** should look something like:

**** SIRMOD input files (*.cfg files)** commonly appear with the icon: Otherwise they most commonly look like:

**** SIRMOD output files (*.out files)** are usually represented by the default icon with the *.out extension shown as they are not recognised by Windows.

If the selected file is of the incorrect type ISID will display a warning (Figure 5.7). If this occurs please choose a different file and try again. In some cases users must click in the browse path dialog box (adjacent to the browse button) in order to initiate this check. ISID will attempt to load the specified file regardless of the file extension or format, with unknown results.



This file should have the suffix 'out' instead of 'cfg'. Continue?

Figure 5.7 – File extension warning

When loading the input files it is best to use the ***Browse*** buttons next to the Infilt, IPARM or SIRMOD boxes to select the desired files and then click ***Upload Details*** after both files have been selected. This speeds up the process and reduces the likelihood of selecting the wrong combination of input files. Note that users only need to upload either the Infilt or IPARM file, *NOT* both.

It is not absolutely to load both SIRMOD or Infilt/IPARM files, missing one or the other means that the user is required to enter the missing data manually.

6. Summary Statistics

6.1. Event vs. Furrow statistics

ISID contains two options for calculation of the performance statistics accessed through the ***Calculate Statistics*** drop-down box:

1) Event Based – splits each evaluation into separate events, each may contain any number of furrows. The value of each performance parameter for the event is calculated as the median of all furrows within that event.

2) Furrow Based – splits each evaluation into separate furrows, treating each furrow as an individual data element.

The values of the performance statistics will differ between the two options. Statistics generated using the furrow based option will tend to bias any event with an increased number of measured furrows, i.e. an event with 4 furrows will become 4 times more important than an event with 1 measured furrow. In contrast, the event based stats allocate even weighting to all events, regardless of the number of measured furrows.

It is recommended that users choose the default ***summarise by event*** option unless they fully understand the significance of the potential difference.

6.2. Overview User

The overview level user has no access to site specific details, being limited to searching the database to generate summary statistics. The homepage is divided into two main sections (Figure 6.1); the search filters and the search results.

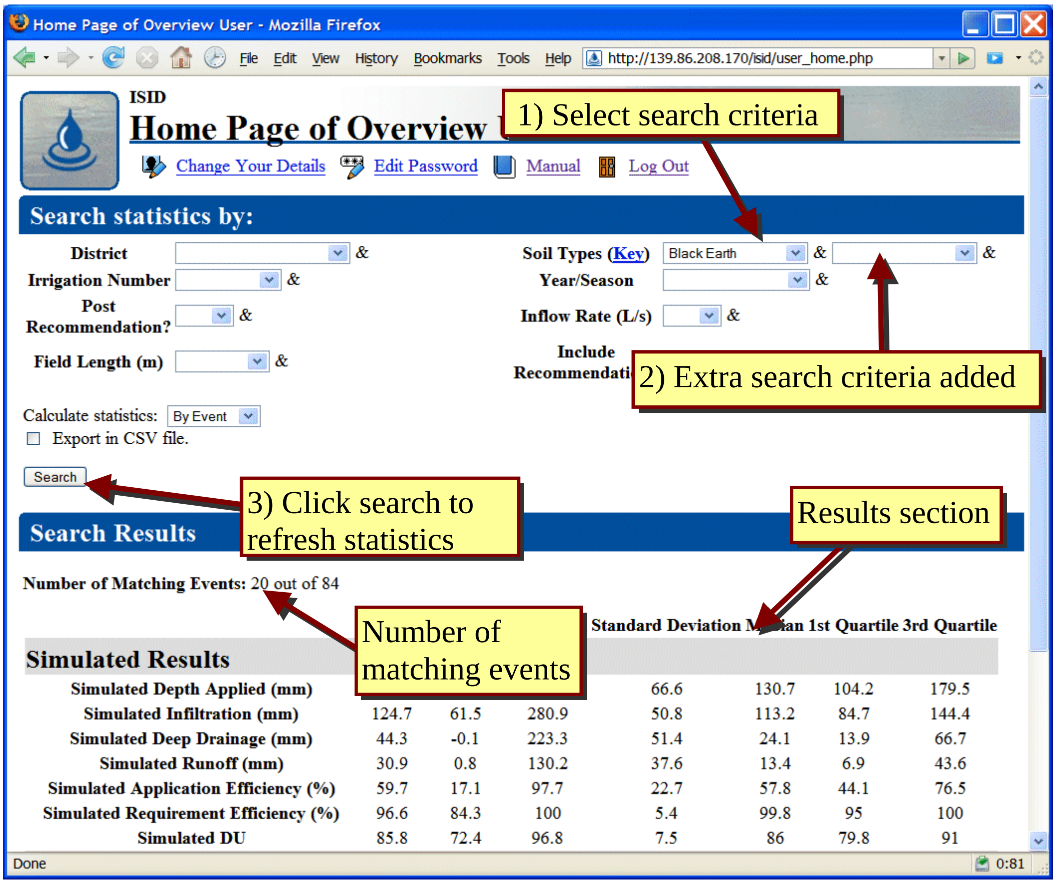
In default mode, ISID searches and generates summary statistics based on all events or furrows contained in the database (omitting those that have been excluded, see section 4.1). The search filters enable users to summarise the results based on a number of defined criteria. Currently searches may be performed based on district, soil type, irrigation no., season, pre/post recommendation, inflow rate and field length or any combination thereof. Some combinations of the search filters may result in ISID failing to provide summary statistics. This may occur due to one of the following:

1. *"There are no evaluations to display that match the given search criteria."*

2. *"Insufficient number of evaluations"*
ISID hides the results whenever the search yields less than a pre-determined number of results (database security measure to maintain anonymity).

Both cases require a widening of the search filters in order to include a larger number of records.

For explanation of each search criteria see the relevant material in section 4.



Search statistics by:

District &

Irrigation Number &

Post Recommendation? &

Field Length (m) &

Soil Types (Key) Black Earth & &

Year/Season &

Inflow Rate (L/s) &

Include Recommendati

Calculate statistics: By Event

☐ Export in CSV file.

Search Results

Number of Matching Events: 20 out of 84

Simulated Results				Standard Deviation	Median	1st Quartile	3rd Quartile
Simulated Depth Applied (mm)				66.6	130.7	104.2	179.5
Simulated Infiltration (mm)	124.7	61.5	280.9	50.8	113.2	84.7	144.4
Simulated Deep Drainage (mm)	44.3	-0.1	223.3	51.4	24.1	13.9	66.7
Simulated Runoff (mm)	30.9	0.8	130.2	37.6	13.4	6.9	43.6
Simulated Application Efficiency (%)	59.7	17.1	97.7	22.7	57.8	44.1	76.5
Simulated Requirement Efficiency (%)	96.6	84.3	100	5.4	99.8	95	100
Simulated DU	85.8	72.4	96.8	7.5	86	79.8	91

Figure 6.1 – Overview user homepage

By default the overview homepage contains a single drop-down box permitting one selection for each search filter. Selecting a value will add an additional drop-down box which can be used to add additional filter conditions.

In Figure 6.1 the soil type "Black Earth" has been selected, ISID adds an extra drop down box allowing the user with room to select an additional soil type.

The ***Number of Matching Events*** gives an indication of the number of events or furrows (depending on the ***Calculate Statistics*** option) that satisfy the current search filters and have been used to generate the summary statistics. The quality of conclusions drawn from these results is determined by the number of matching data points. Statistics based on reduced numbers of matching evaluations should be treated with caution.

6.2.1. Simulated Results

The simulated results section presents summary statistics based on the simulated performance under measured field conditions. As such they provide the best possible estimate of applied depths, efficiencies and uniformities. The results in this table cannot be used to observe the spatial variance expected within individual fields, except to a limited extend in those cases where multiple furrows have been supplied. The min, max, standard deviation, etc represent the variability between the events/furrows included in the database matching the search criteria. As such the min, max and standard deviation will always underestimate the full extend of the variability in respect to the whole field area.

Most people will be familiar with concepts such as the average (arithmetic mean) and standard deviation. However, these statistics can be adversely affected by outliers and skewed values, particularly with low numbers of data points. Probably more useful are the median, 1st quartile and 3rd quartile which are less sensitive to outliers. The median represents the value of a variable which splits the data into two even halves and us calculated by ranking data set in ascending order. The first and third quartiles correspond to the median of the resulting lower and upper halves of the data set, respectively.

Take the following example to illustrate this point:
Application Efficiencies: 20%, 83%, 85%, 86% and 90%.
Mean/Average = 72.8% *Median = 85%*

The average is lower than 4 out of 5 of the events, clearly in this case the median provides the better estimate of the midpoint.

6.2.2. Optimised Simulation Results

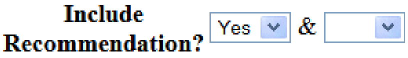
Optimised simulation results (see section 4.7.4) summarises the predicted irrigation performance of the same fields under "user recommended" field management. These results therefore do not necessarily represent the potential "optimal" performance.

Before using the optimised simulation results users must consider the following:

1) The performance estimates are based on suggested field management derived manually via a trial and error process
2) "Optimised" results are only present for limited numbers of the evaluations in the database, hence preventing direct comparisons (unless using the appropriate search filter) between the simulated and optimised values.

The concept of the "optimised" irrigation is difficult to define. The optimal management for one field may be inappropriate and or impossible to achieve for other fields. The optimised/ recommended results do not represent the optimum irrigation but instead the performance of that field under a suggested change to the management practices. The recommended performance aims to record the potential irrigation performance under the adoption of best practice irrigation techniques.

The ***Include Recommendation*** search filter is included to enable valid comparisons between the recommended (optimised) and measured (simulated) irrigation performance.

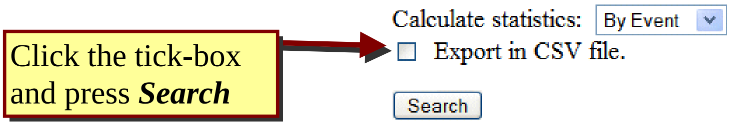


Include Recommendation? Yes &

When using this option the number of matching events and furrows will drop dramatically, often below the minimum threshold count for presentation of results. Recommended results are an optional component of the evaluation, hence the ***Include Recommendation*** functionality is dependent on user's willingness to enter the required data.

6.2.3. *Exporting Results*

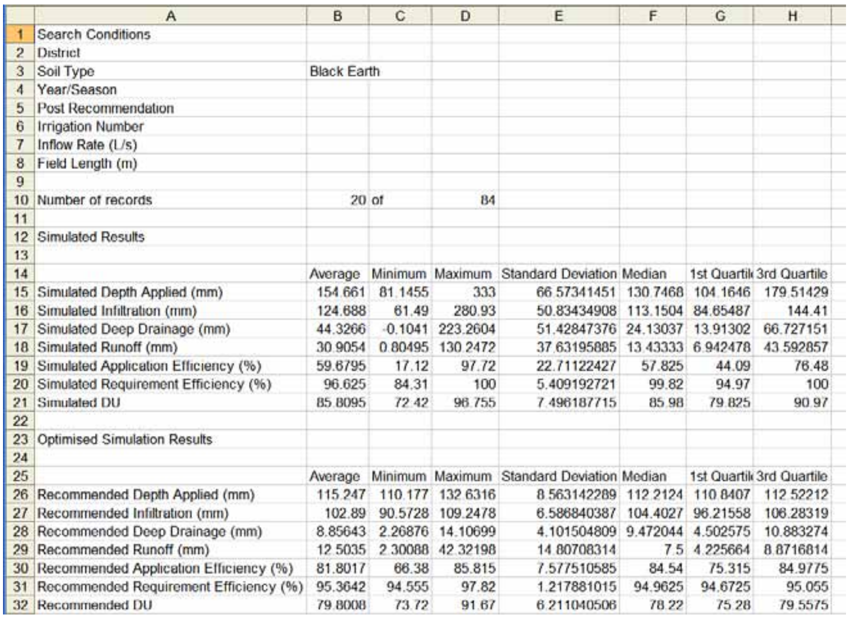
The ***Export in CSV file*** tick box enables users to export the summary statistic results that are currently displayed on screen to a file for later reference. ISID exports the file in comma delimited format with the *csv extension. The resulting files can be opened within any spreadsheet package (e.g. Microsoft Excel) or within a text editor. The file also includes a summary of the search filters used to generate the results.



Click the tick-box and press ***Search***

Calculate statistics: By Event

☐ Export in CSV file.



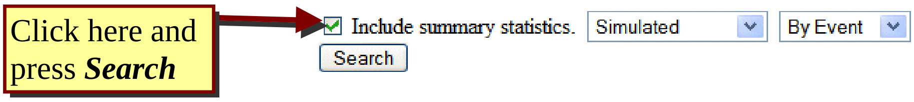
	A	B	C	D	E	F	G	H
1	Search Conditions							
2	District							
3	Soil Type	Black Earth						
4	Year/Season							
5	Post Recommendation							
6	Irrigation Number							
7	Inflow Rate (L/s)							
8	Field Length (m)							
9								
10	Number of records	20	of	84				
11								
12	Simulated Results							
13								
14		Average	Minimum	Maximum	Standard Deviation	Median	1st Quartil	3rd Quartile
15	Simulated Depth Applied (mm)	154.661	81.1455	333	66.57341451	130.7468	104.1646	179.51429
16	Simulated Infiltration (mm)	124.688	61.49	280.93	50.83434908	113.1504	84.65487	144.41
17	Simulated Deep Drainage (mm)	44.3266	-0.1041	223.2604	51.42847376	24.13037	13.91302	66.727151
18	Simulated Runoff (mm)	30.9054	0.80495	130.2472	37.63195885	13.43333	6.942478	43.592857
19	Simulated Application Efficiency (%)	59.6795	17.12	97.72	22.71122427	57.825	44.09	76.48
20	Simulated Requirement Efficiency (%)	96.625	84.31	100	5.409192721	99.82	94.97	100
21	Simulated DU	85.8095	72.42	96.755	7.496187715	85.98	79.825	90.97
22								
23	Optimised Simulation Results							
24								
25		Average	Minimum	Maximum	Standard Deviation	Median	1st Quartil	3rd Quartile
26	Recommended Depth Applied (mm)	115.247	110.177	132.6316	8.563142289	112.2124	110.8407	112.52212
27	Recommended Infiltration (mm)	102.89	90.5728	109.2478	6.586840387	104.4027	96.21558	106.28319
28	Recommended Deep Drainage (mm)	8.85643	2.26876	14.10699	4.101504809	9.472044	4.502575	10.883274
29	Recommended Runoff (mm)	12.5035	2.30088	42.32198	14.80708314	7.5	4.225664	8.8716814
30	Recommended Application Efficiency (%)	81.8017	66.38	85.815	7.577510585	84.54	75.315	84.9775
31	Recommended Requirement Efficiency (%)	95.3642	94.555	97.82	1.217881015	94.9625	94.6725	95.055
32	Recommended DU	79.8008	73.72	91.67	6.211040506	78.22	75.28	79.5575

Figure 6.2 – Sample csv file

6.3. Field Technician/Grower Level

The homepage of the field tech/grower level may look different to the overview user but operates in a similar manner and contains similar results.

The checkbox Include summary statistics displays/hides the simulation results.



Click here and press ***Search***

☑ Include summary statistics. Simulated By Event

When performing a search, the user only has the ability to summarise results of those evaluations entered by the user themselves. Those wishing to conduct searches across the entire ISID database should obtain a separate overview user login username. In addition to the summary the page also contains results for each event, grouped by evaluation or by furrow, grouped by event and evaluation depending on the *By Furrow/By Event* option. This is particularly useful for checking and identifying those furrows with incomplete information.

If you would like to access results for the entire database please contact the NCEA to gain the required username and password.

7. Soil Classification

The majority of soil characteristics vary continuously hence resulting in an infinite number of soil types. To simplify descriptions several classification systems have been proposed. ISID employs the Australian Soil Classification (ASC).

7.1. Alternative Classification Systems

Some common soil classification systems include the great soil groups, factual key system and soil taxonomy orders. Although these classes are not directly compatible with the Australian Soil Classification (ASC) most can be adapted using the table provided in Appendix A. The information provided here is aimed to point out the differences and benefits of the ASC.

7.1.1. Soil Taxonomy

The soil taxonomy system was devised to describe all the soils of the world. The scheme is comprised of 11 soil orders where each is a group of similar soils with a visually distinguishable soil property. Underneath each order the soils are further divided into a series of soil series identifies by characteristics such as climate, thickness of the profile, acidity, mineralogy and other properties of the soil and environment (Singer and Munns 1999). The Soil Taxonomy scheme is somewhat universally accepted hence knowledge of its classification system is often necessary for international publications. Although this system was designed to encompass soils across the globe no Australian soils were included during the development phase. For this reason the relevance of this classification scheme to many soils which are uniquely Australian is questionable (Charman and Murphy 2005).

7.1.2. Great Soil Groups

The Great Soil Group classification is based the field observations of several morphological features such as colour, texture, structure and depth. This system has the major disadvantage of lack of clear boundaries between separate groups (Charman and Murphy 2005). Difficulties commonly arise where particular soils do not fit neatly and must be allocated to a specific group where they may not necessarily belong.

7.1.3. Factual Key

The Factual Key (Northcote 1979) was developed in the 1950’s and 1960’s based on 500 soil profiles across south-eastern Australia. The factual key shares many of the advantages of the Australian Soil Classification such as the distinct definition of the classes according to characteristics of the soil profile. The number of collected soil profiles has increased significantly over the last few decades providing the need for a revised classification scheme.

7.2. The Australian Soil Classification

The Australian Soil Classification (ASC) was proposed to overcome a number of issues with the existing soil classification schemes. The system was developed based on a database of 14000 soil profiles, most of which with laboratory analysis (Isbell 1996). The original database is slightly biased towards Queensland and focuses primarily on agricultural soils, one common criticism of the scheme.

The ASC is a hierarchical system with mutually exclusive classes based on soil attributes relevant to land use management and applicable across all soils found within Australia. Classification is based on the physical and chemical properties of soil horizons rather than being determined by geographical position or parent materials. The classification key enables a new soil to be identified via a logical process of elimination.

7.3. Classifying a Soil Using the ASC (Australian Soil Classification)

7.3.1. Order Classification

The "key to soil orders" in Appendix B provides a good starting point to assign any unknown soil to its appropriate classification. The key should be read in the sequence presented until the appropriate "soil order" class is identified. The key merely serves as a starting point for quick reference, details of the classification along with a description of the parent materials, land uses and geographical distributions can be found in the full version of the Australian Soil Classification (Isbell 1996 and Isbell et a. 1997) or using the online version available at: http://www.clw.csiro.au/aclep/asc_re_on_line/soilkey.htm

7.3.2. Suborder Classification

Colour is one of the first typical observations of the soil, it is interesting to note that the majority of soil minerals are not distinctly coloured. Classification according to colour may appear to be a little crude, however in most cases differences in colour can attributed to changes in soil chemistry. Soil characteristics such as organic matter, iron concentration and moisture content are all strongly related to the soil colour. Generally, the presence of organic matter will darken the soil, the presence of iron is associated with red and yellow colours whilst carbonates produce white shades. Within the ASC, the majority of agricultural soils (e.g. Vertosols) are subdivided within each soil order according to the dominant colour(s) in the B horizon or A and B horizons. Further details are provided in the soil key.

7.4. Re-classification of Cotton Soils for the Australian Soil Classification

The document: "SOILpak for cotton growers" (McKenzie 1998) provides a comprehensive description of the soils most commonly found in the cotton growing regions of Australia. Unfortunately the authors of SOILpak adopted the Great Soil Group classification which in most cases is difficult to re-classify according to the ASC system. The table provided in Appendix A and the material in this subsection can be used as a rough guide to reclassify soils according to the ASC. However, the best approach is to start from first principles using the soil key and the original soil profile.

7.4.1. Clay Soils

A large proportion of the soils found in Australian cotton growing regions can be termed clay soils (i.e. black earths and grey and brown clays) which are classified as Vertosols under the ASC. Vertosols can be generalised as soils high in clay content that exhibit strong cracking upon drying following wetting. Further division into suborders is carried out according to the dominant colour in the A and upper B horizons. For example; black earths become black Vertosols and grey clays become grey Vertosols.

7.4.2. Red Brown Earths

In parts of NSW such as the Macquarie, Namoi and Gwydir Valleys some cotton growing soils are classified as red-brown earths (Great Soil Group). Red-brown earths feature a loamy reddish coloured A horizon (top soil) overlying a red-brown clay B horizon (subsoil). Intuitively the majority of red-brown earths fall into the ASC Chromosol class or more precisely the Red Chromosols. The difficulty is that many of the red-brown earths found in southern Australia are in fact sodic in their upper B horizons and hence should be classified as Sodosols (Isbell et. al. 1997). For further complication, some red-brown earths are acidic in their upper B horizon and therefore should be classified as Kurosols. Kurosols are not commonly associated with cotton growing however agricultural practices may cause Chromosols and Sodosols to take on the properties of Kurosols (McKenzie 1998).

7.4.3. Solodic Soils

Solodised solonetz and solodic soils can be identified as those with loamy topsoil (A horizon) that can be anywhere from neutral to strongly acidic overlying an alkaline to strongly alkaline subsoil (B horizon). The lower part of the A horizon (A2) is bleached with a clear texture contrast between the A and B horizons. As for the red brown earths, solodised solonetz and solodic soils may be classified as either Chromosols, Sodosols or Kurosols using the ASC system. In most cases they will be classified as Yellow at the suborder level with the possibility of other colours (except red).

7.4.4. Alluvial Soils

An alluvial soil can be considered as any soil formed as the result of deposition from a river flowing along a flood plain. Alluvial deposits are usually considered as those deposited closest to the river and hence they tend to have a lighter texture than soils which formed further from the river bank. In the cotton SOILpak (McKenzie 1998) alluvial soil refers to any soil that occurs on young alluvium (deposited in the recent geological past). They may have variable organic contents in the upper A horizon overlying layers of gravel, sand, loam and clay. Attempting to quickly assign alluvial soils to an appropriate ASC class is difficult. Alluvial soils may be classed as Rudosols or Tenosols for the more recent deposits or Chomosols or Kandosols for the more developed profiles. The requirement to reclassify from first principles is particularly apparent for alluvial soils due to the wide variety of potential soil types.

7.5. Glossary of Soil Terms

The Australian soil classification is developed for those who have a good understanding of soil physics and soil chemistry. As such it contains a number of terms and concepts that will not be common knowledge for many users.

A horizon – Mineral horizon closest to the soil surface containing some decomposed organic matter. Often termed the top soil

Apedal – A soil with no apparent physical structure being either single grained or massive.

B horizon – The layer below the A E and O horizons which is primarily comprised of weathered parent material, often termed the subsoil. The B horizon is characterised by the accumulation of Fe, Al, carbonate, gypsum, Si, clay or humus particles from the overlying layers.

B1 horizon – A transitional zone between the A and B horizons, dominated by the B horizon but having some characteristics of the A horizon.

B2 horizon – The major part of the B horizon and usually the layer with the strongest pedological development.

Bh horizon – A layer within the B horizon which is dominated by organic or humic material (hence the symbol “h”). The Bh horizon is characterised by high organic and aluminium content but low iron content.

Bhs horizon – A layer within the B horizon with humosequic properties, i.e. having high organic, aluminium and iron contents. The organic matter is often present as streaks or patches.

Bs horizon – A layer within the B horizon with a dominance of iron compounds.

C horizon – Layers underneath the B horizon, commonly weathered parent material and little effected by soil forming processes.

Calcareous – Soils with high calcium carbonate content. In almost all cases the carbonate will produce an effervescence reaction on addition of hydrochloric acid.

Cemented pan – A hardened or “cemented” soil horizon, a feature of a strongly developed B horizon.

E horizon – Mineral horizon characterised by the loss of Fe, Al, carbonate, Si, clay or humus particles.

ESP – Exchangeable sodium percentage. Measured as a percentage of exchangeable sodium compared to the total cation exchange capacity of the soil. Related to the SAR, *see sodic*.

Horizon – A horizontal soil layer with distinct characteristics.

Lenticular – Soil structure where the peds are arranged in a circular or elliptical fashion bounded by curved faces, considered to be lens shaped. This term usually refers to Vertosols.

Melacic – Refers to a dark coloured horizon at the soil surface that has too little organic content to be classed as a humose layer. The layer must be greater than 0.2m thickness and have a pH less than 5.5.

Pedodenic/Pedological – A term used to describe soil forming processes.

Profile – The profile is a vertically exposed cross-section of the soil. It is usually necessary to take a profile to classify a soil rather than observation of the surface layer.

Saprolite – Chemically weathered rock that has maintained the characteristics that were present in the parent material.

Self mulching – A term used to describe the structural behaviour of some clay soils. These soils tend to form peds at the soil surface that fall apart upon drying to form a surface mulch.

Slickenslides – A structural feature common found in the B horizon of Vertosols where soil masses slide past each other resulting in smooth polished surfaces.

Sodic/Sodicity – High concentration of sodium (Na) ions. Classed as those soils with a high exchangeable Na ratio compared to the concentration of calcium (Ca) and magnesium (Mg) ions, sometimes measured in terms of the SAR (sodium adsorption ratio) or ESP. Sodicity is usually associated with the subsoil and results in dispersion of the soil particles upon wetting.

Solum – The upper and most weathered layers of the soil profile namely the A, E and B horizons**.**

Strongly acid – A soil having a pH of less than 5.5.

Subplastic – A soil that appears to become more clayey and harder to work with prolonged kneading (10 minutes).

Tenic – Used to describe a layer weakly developed layer in the B horizon which contrasts to both the overlying and underlying soil horizons in terms of texture, structure, colour and or segregations in pedogenic origin.

Texture – The size or coarseness of a soil material, determined by the ratios of sand, silt and clay in a sample. Texture classes are commonly associated with the clay content of the soil.

Vertic – Subsoils with clay contents greater than 35% which experience significant shrinking on drying and swelling on wetting and hence are usually identified by their cracking behaviour. Vertic soils are associated with slickenslides and lenticular peds.

8. References

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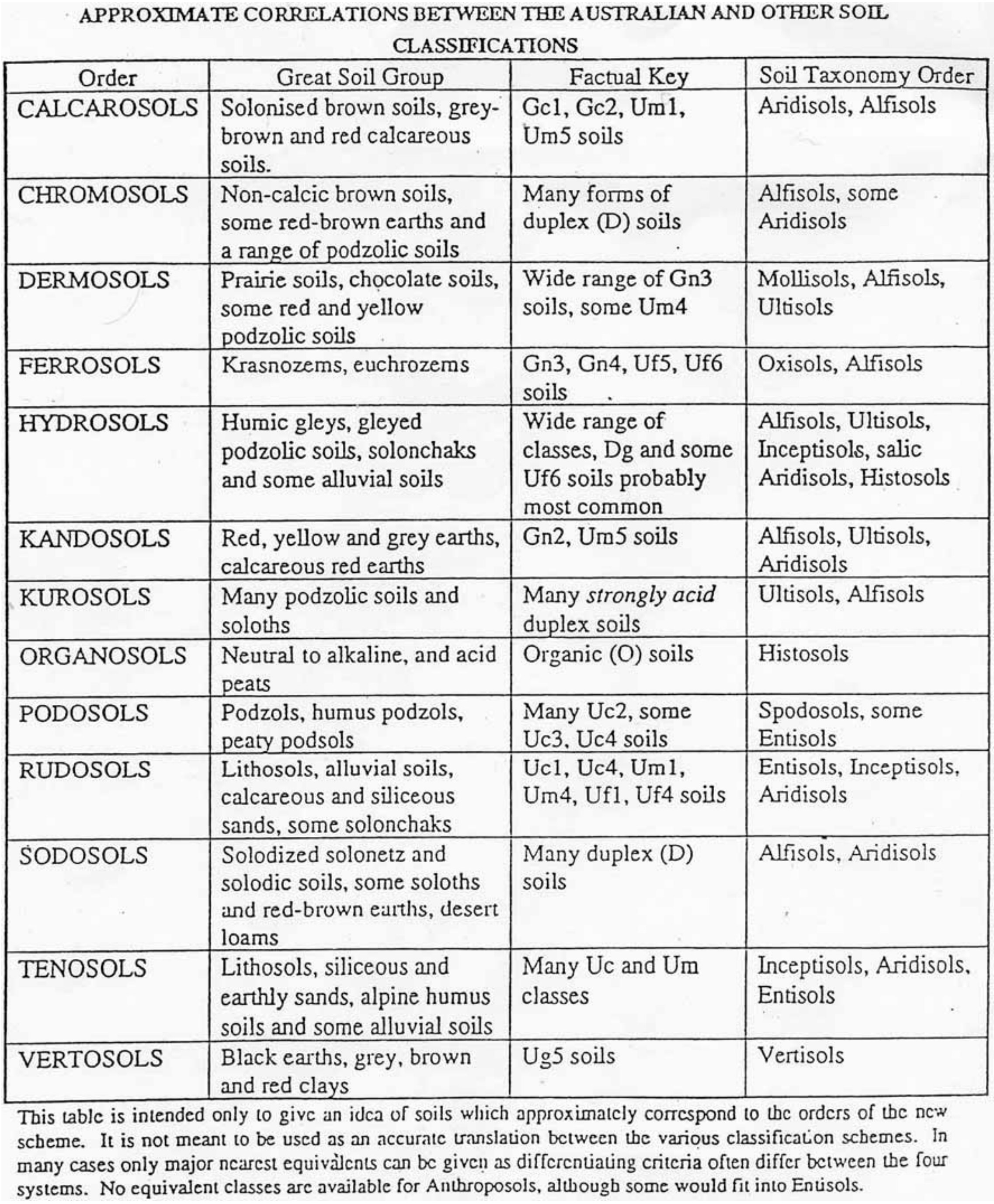
Appendix A – Comparison of the Australian Soil Classification with Other Naming Systems



APPROXIMATE CORRELATIONS BETWEEN THE AUSTRALIAN AND OTHER SOIL CLASSIFICATIONS

Order	Great Soil Group	Factual Key	Soil Taxonomy Order
CALCAROSOLS	Solonised brown soils, grey-brown and red calcareous soils.	Gc1, Gc2, Um1, Um5 soils	Aridisols, Alfisols
CHROMOSOLS	Non-calcic brown soils, some red-brown earths and a range of podzolic soils	Many forms of duplex (D) soils	Alfisols, some Aridisols
DERMOSOLS	Prairie soils, chocolate soils, some red and yellow podzolic soils	Wide range of Gn3 soils, some Um4	Mollisols, Alfisols, Ultisols
FERROSOLS	Krasnozems, euchrozems	Gn3, Gn4, Uf5, Uf6 soils	Oxisols, Alfisols
HYDROSOLS	Humic gleys, gleyed podzolic soils, solonchaks and some alluvial soils	Wide range of classes, Dg and some Uf6 soils probably most common	Alfisols, Ultisols, Inceptisols, salic Aridisols, Histosols
KANDOSOLS	Red, yellow and grey earths, calcareous red earths	Gn2, Um5 soils	Alfisols, Ultisols, Aridisols
KUROSOLS	Many podzolic soils and soloths	Many *strongly acid* duplex soils	Ultisols, Alfisols
ORGANOSOLS	Neutral to alkaline, and acid peats	Organic (O) soils	Histosols
PODOSOLS	Podzols, humus podzols, peaty podsols	Many Uc2, some Uc3, Uc4 soils	Spodosols, some Entisols
RUDOSOLS	Lithosols, alluvial soils, calcareous and siliceous sands, some solonchaks	Uc1, Uc4, Um1, Um4, Uf1, Uf4 soils	Entisols, Inceptisols, Aridisols
SODOSOLS	Solodized solonetz and solodic soils, some soloths and red-brown earths, desert loams	Many duplex (D) soils	Alfisols, Aridisols
TENOSOLS	Lithosols, siliceous and earthly sands, alpine humus soils and some alluvial soils	Many Uc and Um classes	Inceptisols, Aridisols, Entisols
VERTOSOLS	Black earths, grey, brown and red clays	Ug5 soils	Vertisols

This table is intended only to give an idea of soils which approximately correspond to the orders of the new scheme. It is not meant to be used as an accurate translation between the various classification schemes. In many cases only major nearest equivalents can be given as differentiating criteria often differ between the four systems. No equivalent classes are available for Anthroposols, although some would fit into Entisols.

Appendix B – Key to Soil Orders

ISID

The Australian Soil Classification – Key to Soil Orders

The information contained in this key has been copied from the Australian Soil Classification (Isbell 1996). For full description of the soil classes go to: http://www.clw.csiro.au/aclep/asc_re_on_line/soilkey.htm

In order to classify a given soil profile, read the following descriptions in order until the correct soil type is identified. Definitions of the soil terms can be found in the ISID user manual

Organosols

Soils that are not regularly inundated by saline tidal waters and either:

1. Have more than 0.4 m of organic materials within the upper 0.8 m. The required thickness may either extend down from the surface or be taken cumulatively within the upper 0.8 m; or
2. Have organic materials extending from the surface to a minimum depth of 0.1 m; these either directly overlie rock or other hard layers, partially weathered or decomposed rock or saprolite, or overlie fragmental material such as gravel, cobbles or stones in which the interstices are filled or partially filled with organic material. In some soils there may be layers of humose and/or melacic horizon material underlying the organic materials and overlying the substrate.

Podosols

Other soils that have a Bs (dominance of iron), Bhs (high organic, aluminium and iron contents) or Bh (high organic and aluminium but low iron content) horizon layers within the B horizon (see Podosol diagnostic horizons). These horizons may occur either singly or in combination.

Vertosols

Other soils that:

1. Have a clay field texture or 35% or more clay throughout the solum except for thin, surface crusty horizons 0.03 m or less thick, and
2. Unless too moist, have open cracks at some time in most years that are at least 5 mm wide and extend upward to the surface or to the base of any plough layer, self-mulching horizon, or thin, surface crusty horizon, and
3. At some depth in the solum, have slickensides and/or lenticular peds.

Vertosols are further classified using the dominant colour in the upper 0.5m of the profile.

Hydrosols

Other soils that are saturated in the major part1 of the solum for at least 2-3 months in most years (ie. includes tidal waters).

Kurosols

Other soils with a clear or abrupt textural B horizon and in which the major part of the upper 0.2 m of the B2 horizon (or the major part of the entire B2 horizon if it is less than 0.2 m thick) is strongly acid (pH<5.5).

Kurosols are further classified using the dominant colour in the upper 0.2m of the B2 horizon.

Sodosols

Other soils with a clear or abrupt textural B horizon (contrast to the A horizon) and in which the major part of the upper 0.2 m of the B2 horizon (or the major part of the entire B2 horizon if it is less than 0.2 m thick) is sodic (ESP>6) and is not strongly subplastic (subplastic soils appear to become more clayey and harder to work after kneading). .

Sodosols are further classified using the dominant colour in the upper 0.2m of the B2 horizon

Chromosols

Other soils with a clear or abrupt textural B horizon (contrast to the A horizon) and in which the major part of the upper 0.2 m of the B2 horizon (or the major part of the entire B2 horizon if it is less than 0.2 m thick) is not strongly acid.

Chromosols are further classified using the dominant colour in the upper 0.2m of the B2 horizon.

Calcarosols

Other soils that are either calcareous throughout the solum - or calcareous at least directly below the A1 or Ap horizon, or within a depth of 0.2 m (whichever is shallower). Carbonate accumulations must be judged to be pedogenic, ie. are a result of soil forming processes in situ (either current or relict) in contrast to fragments of calcareous rock such as limestone or shell fragments. See also calcrete.

Ferrosols

Other soils with B2 horizons in which the major part1 has a free iron oxide content greater than 5% Fe in the fine earth fraction (<2 mm). Soils with a B2 horizon in which at least 0.3m has vertic properties are excluded.

Dermosols

Other soils with B2 horizons that have structure more developed than weak throughout the major part1 of the horizon.

Dermosols are further classified using the dominant colour in the upper 0.5m of the B2 horizon.

Kandosols

Other soils that:

1. Have well-developed B2 horizons in which the major part is massive or has only a weak grade of structure, (compare with tenic B horizon and cemented pans), and
2. Have a maximum clay content in some part of the B2 horizon which exceeds 15% (ie. heavy sandy loam, SL+).

Kandosols are further classified using the dominant colour in the upper 0.5m of the B2 horizon.

Rudosols

Other soils with negligible (rudimentary) pedological organisation apart from the minimal development of an A1 horizon or the presence of less than 10% of B horizon material (including pedogenic carbonate) in fissures in the parent rock or saprolite. The soils are apedal or only weakly structured in the A1 horizon and show no pedological colour change apart from darkening of an A1 horizon. There is little or no texture or colour change with depth unless stratified or buried soils are present. Cemented pans may be present as a substrate material.

Tenosols

Soils that do not fall into the above categories. These soils generally have weak pedologic organisation apart from the A horizon.

References:

Isbell R. F. (1996). *The Australian Soil Classification.* CSIRO, Melbourne.

APPENDIX 5

Questionaire: Using HydroLOGIC to benchmark water use

Cotton Catchment Communities CRC
Extension Water Focus Team
Name: ______________________
Location: ____________________
Date: ________________________

Are you aware of the purpose of this study and happy to provide benchmark information? ____

1. Have you used HydroLOGIC at all?
    a. If yes then please continue this survey.
    b. If no then please go to question 10

2. Have you used HydroLOGIC in previous years to estimate crop water use after harvest (benchmark) on your farm or clients farms? ☐ Yes ☐ No
    a) How many seasons? ________________________________
    b) If you are a consultants - How many farms? ________________
    c) Will you be using HydroLOGIC to estimate crop water use crops from the 2006/07 season? ______________________________
        a. If not why not? ________________________________
        ____
        ____

3. Have changes been made to irrigation management following a HydroLOGIC benchmarking operation? ☐ Yes ☐ No
    a. What type of changes? _________________
    ____
    ____
    ____

4. Have you compared water use figures across fields and between farms? ☐ Yes ☐ No
    a. Can this be made easier? _________________
    ____
    ____
    ____

5. Have the HydroLOGIC crop water use reports (benchmark reports) matched your thoughts and figures on individual fields water use?

____
____
____
____

6. What other techniques or software have you used to compare water use between fields?

____
____
____
____

7. Have you found the HydroLOGIC software easy to use?
   a. Which areas of the software could use some work and why?

____
____
____
____

8. Have you found the HydroLOGIC inputs easy to collect?
   a. If not then which inputs take the most time?

____
____
____
____

9. Have you used HydroLOGIC to help with decisions about:
   a. ☐ Planting date decisions?
   b. ☐ First irrigation
   c. ☐ Irrigation scheduling?
   d. ☐ Last irrigation?
   e. ☐ Limited water options?
   f. ☐ Others? ______________________________
   ____

10. Do you see any opportunity to use HydroLOGIC assist in crop management? ☐ Yes ☐ No
   a. In which area? ________________
   ____

11. Would you like to learn more about using HydroLOGIC to help with these types of decisions? ☐ Yes ☐ No
    a. How would you like to learn more?

12. Other comments about HydroLOGIC or benchmarking water use in general?

Thank you for your participation!