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A plain English summary

Irrigation is an important component of successful production of cotton. The irrigation water is scarce and the demand for irrigation water is continuously increasing as the area under irrigation expands. With increasing demand, on-farm water use efficiency has become an important issue due to competition between domestic, industrial, livestock and irrigation as well as environmental. This has imposed increased significance on water use efficiency of Australian cotton farms beyond the need to maximise returns from a limited resource.

The purpose of this project was to assess the current status of water use efficiency of the cotton industry at both crop and farm level using historical water management information from commercial producers and existing farming system trials. The information gathered from producers included neutron moisture meter readings, dates of sowing, harvesting and irrigation, yield, amount of irrigation water inputs and weather data. Data from existing farming system trails at ACRI and the CRC farming system sites were used to investigate the effect of farming systems on cotton crop water use efficiency.

Around 200 individual sets of field data were analysed to estimate seasonal evapotranspiration and the actual fraction of irrigation water used by the crop. Water inputs at the farm level, actual crop water use, production efficiencies of water and quantitative water efficiencies at the farm level were calculated for the major cotton growing areas. The observed average crop water use efficiency was 2.5 kg/mm/ha (1.1 Bales/ML) and the average farm level irrigation efficiency was 57% but both showed a large variability. Despite the high efficiency in terms of return per unit of water used there is room for further improvement in crop water use efficiency and irrigation efficiency in many cotton farms. Using the knowledge and experience gained from this project, an integrated water management system will be developed to improve the water use efficiency in cotton farms.

Background to the project

Water use efficiency is a key issue for the Australian cotton industry. For the individual producer the focus is to maximise returns from the limited water resource. For the industry, to secure a fair water allocation, maintain the long-term economic and production sustainability and to create a constructive public perception with respect to environmental concerns are vital. The primary requirement to address these issues are reliable estimates of water use and water use efficiency which truly represent the industry. Industry wide estimates of actual crop water use, quantities of water input from different sources and the efficiency with which this was used were not available. However, valuable historical water mauagement information existed with some commercial producers and with the existing farming system trials at ACRI and the CRC farming systems sites. The major task of this project was to use this information to evaluate the current water use efficiency of the cotton industry. A survey was conducted to collect historical water management information representative of each of the major cotton growing areas. A unique standardised method was developed and used to analyse data across the industry which facilitated the valid comparison of water use efficiencies between properties and valleys.

The objectives and the extent to which these have been achieved

Collect historical water management data from commercial cotton producers across the industry.

More than seventy cotton producers and consultants representing major cotton growing areas were approached to participate in this project. These farmers were selected with the help of cotton extension officers. The collection of data from farmers was not easy as most of the farmers either do not measure water inputs and outputs or records are not properly maintained. About 35% of approached farmers responded positively in this survey. Data were collected from twenty-five farms including xis farms from Namoi valley, eight farms from Gwydir valley, two farms from Macquarie valley, five farms from Emerald, three farms from Darling Downs and one from the McIntyre valley. This data was compiled, analysed and results are presented in this report.

Collect and compile water management data from the existing farming system trials at ACRI and CRC.

Data from a number of farming systems trials were available for the analysis at the ACRI or operated within the CRC. One of the objectives of this project was to investigate the effect of farming systems on crop water use efficiency. The available information from the farming systems experiments was collected and analysed for the last few seasons with the collaboration of site controllers.

The historical data from the long-term rotation trial of Dr. Nillantha Hulugalle (NSW Agriculture) at ACRI for the last five seasons were compiled and analysed to investigate the effect of crop rotation on crop water use efficiency. The preliminary results of this analysis have been published in the ACGRA conference proceedings of 1998 and the paper is attached to this report. The summary of water use and crop water use efficiencies is presented in the results section of this report.

The data from the CRC trial at Beechworth were processed and analysed with the help of Grant Robert (CSIRO Plant Industry). There were some discrepancies in the Beechworth historical water management data. These problems were rectified in the last season and the data have heen compiled and analysed. The results have been presented in this report. The data from ultra narrow row trial on the Breeza plains were also analysed with the collaboration of Mark Hikman (CRC). Data from the dryland farming systems trial data at Warra have also been collected with the help of Greg Salmond (QDPI). Analysis is still in progress.

Collect all weather data from producers if possihle or use nearby meteorological stations.

Climatic data for the participating cottou farms were collected. This information was required for estimation of evapotranspiration via the energy balance. Daily rainfall figures were used in the water balance model in estimating seasonal crop water use described below. There was considerable spatial variability in rainfall in the cotton growing areas. Therefore rainfall figures were collected from farm records and the other weather data were collected from the nearest meteorological stations. This was adequate, as there is less spatial variability in these data.

Develop desktop software tool to estimate water use and efficiencies.

A desktop methodology was developed to assess the water use efficiency of the cotton industry using the information available from producers. The actual seasonal water use by the crop and the contributions from irrigation, within season rainfall and the moisture stored during winter were estimated. This allowed the calculation of crop water use efficiency, irrigation efficiency, rainfall efficiency and other farm water use efficiencies as described below.

The volumetric soil moisture in the soil profile, estimated using neutron probes, as used as the primary input to estimate seasonal evapotranspiration (ET). However the probe data alone were not sufficient to estimate seasonal ET as measurement were not taken regularly enough in commercial crops. The data were augmented by developing a daily soil water balance model, based on the energy balance approach, to fill the gaps between neutron probe observations. A spreadsheet procedure was devised in which the actual measurements were used wherever possible and the water balance calculation inserted as necessary. This approach was used to estimate daily ET, net irrigation intakes and effective rainfall in the irrigated cotton crops during the growing season.

Estimate water inputs from different sources

The three major water inputs to a typical cotton farm are seasonal rainfall, irrigation and moisture stored in the soil. Records of the irrigation inputs at the farm gate were collected from participating producers. In contrast, only a few producers had records of the quantities of on-farm harvested water. Speculated values provided by the producer were used when harvested figures were not available. The "in season" rainfall and its contribution to meet the crop water requirements were calculated at the farm level. The soil moisture reserves depleted during the season were also estimated and average figures were calculated for the different valleys.

Assess the current status of water use efficiency

A number of water use efficiency indices were defined and calculated at the crop level and farm level and averages for each valley derived. The definitions of these indices are given in the methodology section. These indices were used to assess the current status of water use efficiencies and make comparisons between properties and valleys. The comparison between seasons was also performed for the last few seasons.

The methodology and a justification for the methodology used

Defining water use efficiency

The first task of this project was to define water use efficiencies. A large number of different water use efficiency indices are being used by scientists and water managers and these indices vary according to inputs, outputs and the boundary conditions. A few key water use efficiencies of the cotton industry have been illustrated in Figure 1. Water use efficiency indices can be defined under two major categories: production efficiencies and quantitative efficiencies. Production efficiency is the amount of yield produced per unit amount of water used as defined at some level in the production system. A quantitative efficiency is the amount of water output per unit water input at different points of the farm. Both production and quantitative efficiencies are important to assess the system in order to maximise the economic returns from the limited water resource. Due to the complexity of the systems it is not feasible to calculate all the water use efficiency indices that are possible. However, a the most practical and useful water use efficiency indices were defined and calculated in this project. The time scale used in calculating efficiencies is specified as the growing season, which is the period from the date of sowing to the date of harvesting. The water losses generally occurring in storage outside the growing season were not included in this efficiency calculation.

Production aspects of water use efficiencies

Production efficiencies are water use efficiency indices defined in terms of yield per unit amount of water input. This can be defined at many different levels. At the leaf level, the amount of CO_2 fixed per unit amount of water transpired per unit leaf area during a particular time period is known as physiological water use efficiency. At the farm level the number of bales produced per unit amount of water used can be calculated. Production efficiencies can be simply transformed into economic efficiencies by converting yield figures into market prices.

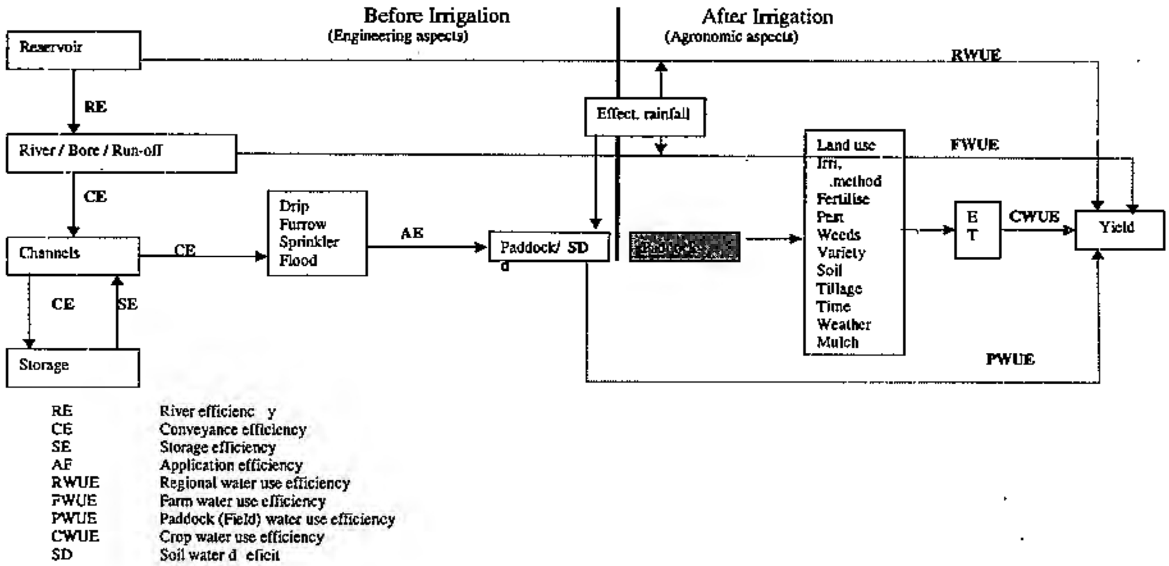


Figure 1. Some key water use efficiencies within a typical cotton farm

For an irrigated cotton farm, production efficiency efficiencies can be calculated as lint yield per total water input or as yield per unit of irrigation water input. The total water inputs in an irrigated cotton farm includes water pumped from rivers and bores, the amount used from storage reservoirs, water harvested during the season, effective rainfall and soil moisture reserves depleted during the season. The yield produced per megalitre of irrigation water input is commonly used by farmers to assess their water use efficiencies. However, this index is heavily dependent on the amount of rainfall received during the growing season and the amount of soil reserves used and so is less valuable for comparing between seasons or locations.

The production efficiency indices used in this project are defined below.

Crop level: *Crop water use efficiency (CWUE):* This is the lint yield (kg) produced per millimetre of water evapotranspired from a cotton field during the growing season.

CWUE (kg/ha/mm) = lint yield (kg per ha) / seasonal ET(mm)

This index is important to evaluate how efficiently the crop produces lint yield with the amount of water consumed as evapotranspiration during the growing period. This can also be expressed in bales per megalitre.

Field level: *Field water use efficiency* is the amount of lint yield produced per unit volume of total water input to the paddock. The field level water use efficiency calculation requires measurement of water inputs and outputs at the field level. This assessment is important, as the field is the primary management unit in a farm. This efficiency depends on physical, chemical and biological characteristics of the paddock and application efficiency of irrigation water.

Field water use efficiency = Yield / Total water input to the paddock

The yield out per unit irrigation water input can also be calculated at the field level. However, the field level irrigation efficiency figures were not calculated since field level water inputs records were not available with most of the producers.

Farm level: *Farm water use efficiency (FWUE):* This is the amount of lint (bales) produced per megalitre of total water used at the farm level. The farm water use efficiency can be calculated considering either total water or irrigation water used and total farm production.

FWUE (total water)=total yield (bales)/total seasonal water usage (ML)

FWUE (irrigation water)=total yield (bales)/applied irrigation water (ML)

At regional level: The amount of bales produced per ML of irrigation water used at regional level can be calculated by considering the amount of lint processed at the gin and the amount of irrigation water released from the dam or the amount of irrigation water pumped from rivers and bores. The economic efficiency of water at regional level can be calculated by the amount of dollars produced per unit amount of water depleted within the region during a certain period of time.

Quantitative water use efficiencies

In an irrigation system, efficiency can be calculated as the ratio of water inputs and water outputs at different points of the system. Storage efficiency, conveyance efficiency, application efficiency and distribution efficiency are commonly used quantitative water use efficiencies. In this project, farm level irrigation efficiency over the growing season was calculated as the percentage of irrigation water actually used by the crop (ET) relative to the total irrigation water inputs at farm level during the growing season. This efficiency is different from the efficiency of a single irrigation event at the field level. On many occasions efficiency figures based on a single irrigation have been misused to make assessments and recommendations at the farm level or regional level. The efficiency of a single irrigation is calculated from the amount of water delivered to the field and the amount used through crop evapotranspiration.

Water multiplier effect. Irrigated cotton farms use multiple use-cycle systems, as it is a common and essential practice to recirculate water within the farm in many places. Multiple use cycle systems are systems where seepage, operational spillage and run off from the tail end, which are often thought of as losses can be reused in the same farm or another part of the command area. For such systems, because of multiple reuse the supply of water to the farm can be less than the total (aggregate) the amount of water actually applied to crops in successive irrigations. Because of this multiplication effect the whole farm efficiency of multiple use-cycle system is higher than the efficiency of individual use-cycles or fields.

On farm water harvesting of rainfall: This needs to be taken into account when assessing the whole farm efficiency. Producers are not allowed to discharge the run off from the farm. Rather it is captured and stored for future use. The harvested water thus becomes a part of the irrigation water supply and can be counted as an irrigation component in calculating irrigation efficiency.

Practical problems arise in estimating the on farm harvested water as it is not easy to meter every single run-off flow in a farm. The harvested water can be estimated by measuring the water level in the storage before and after a rainfall event. If the efficiency is calculated only for the growing season, the amount of water used from the farm storage should also be included in the assessment. Taking all these factors into account the farm level irrigation efficiency can be defined as follows.

$$IE = \frac{CropET - RF_E - SM_D}{\text{Total water pumped from rivers and bores} + \text{harvested water}}$$

IE – Irrigation efficiency, **CropET** - Total evapotranspiration
RF_E - Effective precipitation, **SM_D** - Soil moisture depletion

This efficiency index can be reliably used to make comparisons between properties and seasons. Some people use the number of bales produced per irrigation input to make comparison between properties or seasons. The analyses performed in this project shows that the number of bales produced per irrigation water used is not an appropriate index to make comparisons between properties or seasons. The analysis is presented in Appendix 1. The irrigation water saving in a farm can also be accurately assessed by farm level irrigation efficiency index provided.

Collection of historical water management data

Historical water management data for the last two to three years were collected from approximately 25 farmers representing major cotton growing areas. The following information was collected from producers for the last few years depending on availability.

Field level (3-4 fields per farm per season):

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

Farm level:

- On farm daily rainfall data
- 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)

Other than daily rainfall, the climatic information required for the analysis was collected from the nearest meteorological station and the Cotton CRC database.

Farmers were contacted with the help of extension officers. At the beginning a letter was sent to participating farmers describing the project and its objectives. Then the farms were visited to provide details of the information required for assessment of on-farm water use efficiencies. The required guidance was provided to help growers to compile their measurement of water inputs and other relevant data records. Subsequently a number of farm visits were made during the data collection. Sometimes confidentiality agreements had to be made, as some farmers were reluctant to have their farms specifically identified in reports and this request has been respected.

The collected information were variable in uniformity and consistency, as they were not measured and recorded in the same manner. Most of the neutron probe data needed significant attention to convert into a nseable format. Some data files collected were in neutron probe software format and these were converted into text format using the special program obtained from a neutron probe software programmer in Sydney (Trevor Finch, Neutron probe software developer). The total volumetric moisture contents in the soil profile in millimetres were extracted from neutron probe data. This was a required input to the seasonal crop water nse estimation model.

Estimation of seasonal evapotranspiration (ET)

Estimation of actual crop water use (ET) is one of the major prerequisites for calculating crop water use efficiency. This was estimated by means of moisture changes in the soil profile during the growing season. As described earlier neutron probe soil moisture readings were used as the basis for estimating ET. However, in most cases, probe readings had been taken at irregular intervals and these readings by themselves were not sufficient to estimate the profile moisture content for the whole season. Therefore, a daily basis water balance model was developed to simulate the moisture content in the soil profile throughout the growing season. Probe readings were used when readings were available to allow a direct calculation of water use and simulated values were used for the missing values. The following water balance equation was used to simulate the moisture content of the soil profile. In this model deep drainage losses are considered negligible.

$$SMC = Pre.SMC + ER + I - ET$$

SMC = soil moisture content, **Pre.SMC** = SMC of the previous day
ER = effective rainfall, **I** = amount of irrigation intake, **ET** = daily evapotranspiration

The modified Ritchie model was used to estimate the daily evapotranspiration. Coefficients as measured for Australian cotton fields by Peter Cull and Brian Hearn (Personal Communication) were used. The required climatic information to calculate potential evaporation is daily maximum and minimum temperatures, wet bulb temperature and solar radiation. The details of the method developed in estimating seasonal ET is given in the paper titled "Estimation of Evapotranspiration in the Cotton Industry" which is attached to this report.

A number of assumptions were made in this calculation as accurate modelling was not possible due to unavailability of required information. It was assumed that the soil moisture content at sowing (starting date) was equal to the maximum water holding capacity (WHC) of the soil. The WHC of the soil was estimated from the maximum observed soil moisture content. It was also assumed that the soil could absorb water from a rainfall or an irrigation event until its maximum water holding capacity was reached with the rest of the water leaving the system as runoff. The amount of water infiltrating the soil was calculated by taking the difference between maximum WHC and moisture content prior to rainfall or irrigation.

This model computes water use in different components and estimates the amount of transpiration and soil evaporation separately. It also calculates the amounts of irrigation, rainfall and soil reserves used in ET separately during the growing season. These separate estimates allow us to calculate the irrigation efficiency and the effectiveness of rainfall. The amount of soil reserves used is calculated by subtracting the soil moisture content at harvest/defoliation from the soil moisture content at sowing. The data for a number of individual fields' per farm per season were analysed. Average values for the farm were then calculated from individual fields' data.

It is important to note that the procedure adopted in calculating seasonal ET was not designed as a highly precise modelling exercise. This method was developed to allow an adequate estimate of ET to be made based on the available historical water management information with producers. Use of a standard method across the industry was required to allow valid comparisons to be made. The cotton growing areas in eastern Australia have a large variability in soils, climate and other agronomic factors. Consideration of all of these factors for precise modelling of water use estimates across the industry is beyond the expectations of this project.

Calculation of water use efficiencies

The estimated seasonal water use by the crop together with yield figures collected from producers were use to estimate crop water use efficiencies at the field, farm and valley levels. The amount of irrigation water used in ET and the total irrigation water input at the farm level were used to estimate the farm level irrigation efficiency. The number of bales produced relative to total water input and to the irrigation water inputs were also separately estimated. An example of water inputs and water use efficiencies calculated at the farm level is given in Table 1. A number of farms per valley were analysed and the average values for the valleys were calculated.

Table 1 Example of water inputs and water use efficiencies at the farm level

Season	93/94	94/95	95/96	96/97	97/98
Production details					
Area grown ha	3659	2101	2010	3064	3173
Total Production (Bales)	20961	13878	12616	19234	25495
Yield (Bales/ha)	5.7	6.6	6.3	6.3	8.0
Water supply					
Total water pumped (bore)				0	1445
Total water pumped (river)				7447	12100
Total water pumped ML				7447	13545
On farm storage at planting ML				6250	6500
On farm harvested during the season ML				3710	1402
On farm storage at harvestiug ML				3975	4473
Used from farm storage ML				5985	3429
Water used for cereals				2300	2800
Water used for dolichos				0	0
Total irrigation applied on cotton ML				11132	14174
Total irrigation applied on cotton mm				363	447
Rainfall					
Growing season rainfall mm	265	371	462	518	459
Rainfall efficiency	0.91	0.81	0.77	0.67	0.65
Total effective rainfall mm	240	301	354	347	300
Total effective rainfall ML	8794	6334	7114	10642	9512
Run-off mm	24	70	108	171	159
Used Soil reserve mm	118	69	102	119	133
Used Soil reserve ML	4314	1459	2055	3656	4211
Total seasonal water usage ML				25429	27897
Total seasonal water usage mm				830	879
Water use summary					
ML/ha pumped	0.00	0.00	0.00	2.42	4.03
ML/ha effective rainfall	2.40	3.01	3.54	3.47	3.00
ML/ha harvested	0.00	0.00	0.00	1.21	0.44
ML/ha used soil reserve	1.18	0.69	1.02	1.19	1.33
ML/ha total water usage	0.00	0.00	0.00	8.30	8.79
Net irrigation intake mm	340	260	329	226	343
Seasonal crop water use (ET) mm	714	642	786	690	772
Water use efficiency					
Crop water use efficiency kg/mm/ha	1.82	2.33	1.81	2.06	2.36
Crop water use efficieucy Bales/ML	0.80	1.03	0.80	0.91	1.04
Farm crop water use efficiency Bales/ML				0.76	0.91
Bales/ML (Total irrigation water)				1.73	1.80
Whole farm water use efficiecny				0.83	0.88
Irrigation efficiency				0.62	0.77

Total seasonal farm water usage = pumped + used storage + effective rainfall + harvested + soil reserve
Crop water use efficiency = Yield/ET
Farm crop water use efficiency=Yield/ Total seasonal farm water usage
Whole farm water use efficiecny = ET/ Total seasonal farm water usage
Irrigation efficiency = Net irrigation intake (Filled deficit) / Total pumped, used storage & harvested
ML=megalitre, mm=millimetre, ET=Evapotranspiration, kg=kilogram, ha=hectare

Detailed results including the statistical analysis of results

The results of the survey and the assessment of current status of water use efficiency of the cotton industry have been published in a number of local and international publications. All the publications made from this project are attached at the end of this report. A summary of results is presented below.

Details of water inputs

The major sources of water input to a typical cotton farm are in-season rainfall, irrigation and the moisture stored in the soil profile. The amount of irrigation water pumped from rivers and bores and the amount of on-farm harvested water in megalitres (ML) per hectare for the last few season for the different valleys are given in Table 2. The demand for irrigation water is mainly dependent on "in-season" rainfall and the use of irrigation water varies between seasons and regions.

Table 2. The amount of water pumped from rivers and bores and on-farm harvested water per hectare for different valleys

	96/97		97/98		98/99	
Region	Pumped ML	Harvested ML	Pumped ML	Harvested ML	Pumped ML	Harvested ML
Namoi Valley	4.71	0.87	5.16	0.72		
Gwydir Valley	11.86	2.00	12.23	1.33		
Macquarie Valley	7.86	0.19	8.36	1.18		
McIntyre Valley			5.70	0.19	2.18	2.90
Darling Downs			3.13	3.00	2.22	2.20
Emerald			6.30	1.19	3.23	0.67
Mean	**8.14**	**1.02**	**6.81**	**1.27**	**2.54**	**1.93**

The amount of rainfall growing season (October to March) varies significantly between valleys and seasons Table 3.

Most of the cotton growing soils can store up to 1.5ML of available water per hectare and this amonnt is dependent on pre-season rainfall, land use pattern and water holding capacity of the soils. The contribution from in-season rainfall to meet the crop water requirement (effective rainfall) and the used soil moisture reserves are given in Table 4.

Table 3 Long-term annual and seasonal (October – March) rainfall in millimetres.

Region	**No of years**	**Annual**	**Seasonal**
Biloela	107	693	**495**
Bourke	117	350	**202**
Darling Downs (Dalby)	128	673	**451**
Emerald	115	635	**459**
Gwydir valley (Moree)	118	579	**356**
Hillston	113	369	**184**
Macquarie valley (Warren)	114	480	**268**
McIntyre valley (Goondiwindi)	119	620	**389**
Namoi valley (Narrabri)	118	640	**378**
Gunnedah	120	615	**369**
St. George	117	517	**327**

Table 4. Contribution from rainfall and soil reserves for seasonal evapotranspiration in different valleys (SM – soil moisture reserve, RF - rainfall)

	96/97		97/98		98/99	
Region	Effective RF mm	Used SM mm	Effective RF mm	Used SM mm	Effective RF mm	Used SM mm
Namoi Valley	321	132	308	126		
Gwydir Valley	213	124	220	132		
Macquarie Valley	231	114	118	20		
McIntyre Valley			344	48	343	97
Darling Downs			265	182	299	110
Emerald			191	122	378	96
Mean	**255**	**123**	**241**	**105**	**340**	**101**

The actual crop water use

The actual seasonal ET varied considerably from location to location and season to season with the overall average around 740mm. The amount of total ET from individual irrigated cotton fields varied from 600mm to 1000mm over the growing season. The estimated seasonal ET in millimetres for different valleys is given in the Table 5. The highest seasonal mean crop water use of 853mm was observed for the Macquarie valley and the lowest seasonal mean crop water use of 664mm was observed for the Darling Downs. With regards to seasonal variations, the 97/98 season had higher ET values than 96/97 and 98/99 seasons.

Table 5. Seasonal evapotranspiration in millimetres for different valleys as calculated from soil moisture data and simulated figures.

	96/97			97/98			98/99		
Region	**Mean**	Max	Min	**Mean**	Max	Min	**Mean**	Max	Min
Namoi Valley	**764**	968	690	**781**	886	731			
Gwydir Valley	**715**	763	670	**772**	819	732			
Macquarie Valley	**800**	925	752	**853**	888	828			
McIntyre Valley				**771**	779	764	**719**	735	694
Darling Downs				**673**	719	626	**664**	708	623
Emerald				**682**	731	652	**700**	737	677
Mean	**760**			**755**			**694**		

The percentages of rainfall, irrigation and soil moisture reserves contribution to ET are given in the Table 6. These proportions are primarily dependent on the in-season rainfall. Since there are large variations in rainfall between valleys and seasons the irrigation contribution to ET also significantly varies. The results indicate that the antecedent moisture also contributes to ET considerably.

Table 6 Partitioning of ET into different sources of inputs (SM- soil moisture)

	96/97			97/98			98/99		
	rainfall	used SM	irrigation	rainfall	used SM	irrigation	rainfall	used SM	irrigation
Namoi Valley	42%	17%	41%	40%	16%	44%			
Gwydir Valley	30%	17%	53%	28%	17%	54%			
Macquarie Valley	29%	14%	57%	14%	2%	84%			
McIntyre Valley				45%	6%	49%	48%	13%	39%
Darling Downs				39%	27%	33%	45%	17%	38%
Emerald				28%	18%	54%	54%	14%	32%
Mean	**34%**	**16%**	**50%**	**32%**	**14%**	**53%**	**49%**	**15%**	**36%**

Crop water use efficiency (CWUE)

Crop water use efficiencies were calculated from the producers' yield data and estimated seasonal ET. The average yields of the participating farms are given in the Table 7. The average crop water use efficiency observed for all of the valleys and seasons was 2.5 kg/ha/mm with large variability across the valleys (Table 8). The maximum crop water use efficiency of 3.2 kg/ha/mm was observed in the Darling Downs and the lowest of 2.0 kg/ha/mm was observed in the Namoi valley.

Table 7. Average yield from the participated farms (bales/ha)

Region	**96/97**			**97/98**			**98/99**		
	Mean	Max	Min	**Mean**	Max	Min	**Mean**	Max	Min
Namoi Valley	**7.71**	9.08	6.28	**8.32**	9.09	7.80			
Gwydir Valley	**7.32**	7.75	6.28	**8.01**	8.80	7.28			
Mac. Valley	**9.40**			**10.50**	10.80	9.30			
McIntyre Valley	**8.07**			**7.84**			**7.08**		
Darling Downs				**7.99**	8.08	7.90	**8.41**	9.10	7.41
Emerald				**7.60**	8.04	6.85	**7.50**	7.90	7.00
Mean	**8.14**			**8.38**			**7.66**		

Table 8 Crop water use efficiency kg/ha/mm as calculated from actual yield figures and seasonal evapotranspiration.

	96/97			**97/98**			**98/99**		
Region	**Mean**	Max	Min	**Mean**	Max	Min	**Mean**	Max	Min
Namoi Valley	**2.30**	2.47	2.06	**2.43**	2.79	2.03			
Gwydir Valley	**2.33**	2.62	2.06	**2.36**	2.73	2.06			
Macquarie Valley	**2.85**			**2.78**	2.95	2.59			
McIntyre Valley				**2.30**			**2.24**		
Darling Downs				**2.70**	2.86	2.55	**2.88**	3.17	2.55
Emerald				**2.53**	2.80	2.12	**2.45**	2.56	2.34
Mean	**2.49**			**2.52**			**2.52**		

Farm water use efficiency

The farm water efficiency, which is the number of bales produced per unit water input to the farm was also calculated from producers' data. This has been calculated for the total water input and for irrigation water input separately (Table 9). The total water input to the farm includes irrigation, rainfall and soil moisture depleted during the season. The farm water use efficiency for total water varied from 0.38 bales/ML to 1.27 bales/ML and irrigation water varied from 0.43 bales/ML to 3.28 bales/ML.

Table 9. Mean number of bales produced per ML of total water and irrigation water used at farm level

	Total water (Bales/ML)			Irrigation water (Bales/ML)		
Region	**96/97**	**97/98**	**98/99**	**96/97**	**97/98**	**98/99**
Namoi Valley	0.79	0.83		1.60	1.50	
Gwydir Valley	0.45	0.48		0.66	0.63	
Macquarie Valley	0.94	0.93		1.29	1.20	
McIntyre Valley		0.80	0.75		1.33	1.39
Darling Downs		0.79	1.01		1.42	2.14
Emerald		0.72	0.88		1.03	2.04
Mean	**0.73**	**0.76**	**0.88**	**1.18**	**1.19**	**1.86**

Irrigation efficiency

The farm level irrigation efficiency, which is the percentage of irrigation water actually used by the crop as ET compared to the irrigation inputs, was calculated over the growing period. This is an important parameter to evaluate the system in terms of irrigation water losses. The irrigation efficiency calculated in this project is the combination of storage, conveyance and application efficiencies for the whole growing season. The calculated irrigation efficiencies for different valleys are given in Table 10.

Table 10. Average irrigation efficiencies for different valleys

	96/97			97/98			98/99		
Region	**Mean**	Max	Min	**Mean**	Max	Min	**Mean**	Max	Min
Namoi Valley	**0.60**	0.80	0.20	**0.63**	0.79	0.42			
Gwydir Valley	**0.37**	0.62	0.22	**0.42**	0.66	0.32			
Macquarie Valley	**0.66**			**0.68**	0.86	0.50			
McIntyre Valley				**0.67**			**0.60**		
Darling Downs				**0.40**	0.51	0.29	**0.62**	0.76	0.44
Emerald				**0.50**	0.54	0.42	**0.59**	0.70	0.36
Mean	**0.54**			**0.55**			**0.60**		

Results of farming systems trials

ACRI long-term rotation trial

The preliminary results of the long-term rotation experiment at ACRI were published at the 1998 Australian cotton conference. The average seasonal water use and crop water use efficiencies for different treatments for the last few seasons are given in Table 11 and Table 12. The three major treatments in this experiment are (a) intensive tillage with cotton sown in October (b) minimum tillage with cotton sown in October and (c) a cotton/winter-wheat sequence where cotton was sown with minimum tillage in October and wheat with no-tillage in May.

Table 11. The average water used as ET for the ACRI-experiment the last few seasons

Season	**(a) Max.till.con**	**(b) Min.till.con**	**(c) Min.till.rot**
93-94	750	756	733
94-95	747	746	786
95-96	782	796	788
96-97	n/a	n/a	n/a
97-98	754	733	n/a
98-99	672	709	685

Table 12 The average WUE (kg/ha/mm) for the ACRI experiment:

Season	**Max.till.con**	**Min.till.con**	**Min.till.rot**	P-value
93-94	1.72	1.98	2.34	0.007
94-95	1.61	1.79	1.82	0.112
95-96	1.24	1.30	1.40	0.320
96-97	na	na	Na	
97-98	1.83	2.02	Na	
98-99	1.11	1.21	1.45	0.061

This result indicates that there is not difference in total crop water use between treatments. However these results indicate that the rotation of cotton-wheat-fallow had beneficial effects on cotton water use efficiency when compared to continuous cropping. However it is important to note that this advantage was derived from the yield advantage conferred by the rotation and not from differences in water use.

Beechworth results:

There were some problems in the Beechworth historical water management data. The probe readings were not complete and accurate. However the problems were rectified and new water management data are being collected. The last season (99/00) had only the continuous cropping and individual field's data were analysed separately and the water use summary of this trial is given in Table 13.

Table 13: Beechworth 99/00 season results

Plot No:	**4A**	**4B**	**8A**	**8B**	**18A**	**18B**
Yield kg/ha	1218	1218	1331	1331	1442	1442
Total water use (ET) mm	752	740	743	753	732	728
Irrigation used in ET mm	344	335	342	344	333	328
Effective rainfall mm	355	355	357	361	355	354
Utilised soil moisture in ET mm	53	50	43	48	43	45
Total seasonal rainfall mm	453	453	453	453	453	453
Rainfall Runoff mm	98	98	95	92	97	99
Rainfall Efficiency	0.78	0.78	0.79	0.80	0.78	0.78
Water Use Efficiency kg/ha/mm	**1.62**	**1.65**	**1.79**	**1.77**	**1.97**	**1.98**
Proportion of water inputs						
Rainfall	47%	48%	48%	48%	49%	49%
Irrigation	46%	45%	46%	46%	45%	45%
Soil reserves	7%	7%	6%	6%	6%	6%
Proportion of outputs						
Plant transpiration	67%	67%	67%	67%	67%	67%
Soil evaporation	33%	33%	33%	33%	33%	33%

The industry average of crop water use efficiency is 2.5 kg/ha/mm. These results indicate lower crop water use efficiency figures mainly due to continuous cotton. The full assessment of effect of farming systems on crop water use efficiency in this experiment will be done with the 2001 season's data

Discussion of results including an analysis of research outcomes compared with objectives

Water inputs for irrigated cotton farms in the major cotton growing areas were calculated. The amount of total water used for irrigated cotton varied significantly from farm to farm and season to season depending on the geographic location of the farm and climatic variations. The total water used during the growing season varied between 8.5 ML/ha and 17.2 ML/ha. The average amount of irrigation water pumped from rivers and bores for different valleys vary from 2.2 ML/ha to 12.2 ML/ha and the on-farm harvested amounts vary from 0 to 3.2 ML/ha. These differences in total water and irrigation water use may be due to the differences in soil types, climatic conditions, locations, farm layout, water sources and management.

The average crop water use efficiency of 2.5 kg/mm/ha was observed but with a large variability. Hearn's (1997) benchmark for crop water use efficiency is 3kg/ha/mm. According to the results obtained in this project this is an acceptable target for commercial properties. A crop WUE of 3 kg/ha/mm can be achieved by yielding 10 bales per hectare with 750mm seasonal evapotranspiration. A majority of the CWUE figures calculated in this study are below the 3 kg/ha/mm benchmark. This indicates that there is considerable room for improvement of CWUE on some farms. Improving CWUE from 2.5 kg/ha/mm to 3kg/ha/mm with 750mm seasonal ET will result in producing an additional 1.65 bales per hectare with the same water use. Improved CWUE can he achieved not only through improved irrigation management but will also be strongly influenced by other management factors affecting yield such as nutrients, insects, weeds and soil management together with better farming systems.

The overall farm level irrigation efficiency averaged 57% with a large variability. The average irrigation efficiency for the different valleys varied from 37% to 68% for the last few seasons and the observed irrigation efficiencies for individual properties varied from 20% to 85%. The average irrigation efficiencies for 96/97, 97/98 and 98/99 were 54%, 55% and 60% respectively. The results indicate that the irrigated cotton crop actually uses only just above half of the irrigatiou water delivered to the farm and around 40 to 45 percent is lost within the farm. Some proportion of these losses may be contributing to re-charge of the ground water and may thus be being re-used through bore pumping for future irrigations on the same property or in other locations. Some of the low efficiencies observed in this study may be due to conveyance losses, storage loss, application losses or improper scheduling. Identifying these points of losses in the farm and taking necessary action to minimise them will help to improve the irrigation efficiency. The University of Southern Queensland is currently conducting a special research project to develop methods to identify where irrigation water losses occur within the farm.

Assessment of the likely impact of the results and conclusions of the research project for the cotton industry. Where possible include a statement of the costs and poteutial benefits to the Australian Cotton industry and future research needs

Water management is a key issue for sustainable cotton production. The information regarding water use and their efficiencies across the industry collected in this assessment can be used as a basis for future water management activities in the industry. During this project, the awareness of water efficiency issues among cotton producers has been elevated. The measurements of water inputs at various points of the irrigation system and proper maintenance of water use records in the farm were also promoted. Without proper information it would not be possible to assess water use efficiency at any farm.

The desktop method methodology developed in this project can be used to calculate water use efficiencies in the farm office. This provides standard measurements and efficiency calculation methods, thus allowing valid comparisons between fields or properties. Calculation of quantitative efficiencies is also necessary to identify water losses in the system. The production efficiency, particularly calculation of crop water use efficiency is required to assess the system in terms of producing lint yield per unit of water depleted from the farm. The water use efficiency assessment at field and farm level is also required to quantify gains through improved water management activities.

The average crop water use efficiency figures calculated in this project cau be used to evaluate individual properties. The crop water use efficiency is affected by overall water management and other farm management activities. Cropping history and tillage practices can both influence water usage by subsequent crops; whether they are irrigated or not. Fallow water storage can contribute to water use efficiency of irrigated cotton by substituting for water, which would otherwise be provided by irrigation. Similarly, experimental results from the long-term rotation and tillage trial at ACRI indicate that paddock history can also effect water use by cotton through modifying soil structure and macropore distribution.

The results of this project revealed that on average the crop actually used only 57% of irrigation water as evapotranspiration. This indicates that there is a large potential to improve the irrigation efficiency of the cotton industry as the some values were around 86%. However, the economic factors need to be considered in improving quantitative water use efficiencies.

According to the results obtained in this project there is considerable room to improve production efficiency and quantitative water use efficiency at many points. Improvement of production efficiencies at crop level and farm level could make significant difference to the industry in terms of lint yield produced per unit water use at different levels. The improvement of irrigation efficiency will reduce the demand for irrigation water or allow a greater area of cotton to be grown with tbe same amount of water. The opportunity cost of on-farm water loss needs to be considered as every megalitre of irrigation water has the potential to produced 1.4 bales of cotton.

Description of the project technology (e.g. commercially significant developments, patents applied for or granted, licenses, etc)

The main task of this project was to utilise the existing information held by producers and from farming systems trials to assess the current water use efficiency of the cotton industry. A survey was conducted to collect producers' historical water management data across the industry. Less than 35% farmers responded positively mainly because of many growers did not have adequate records to allow evaluatiou of water use efficiency indices.

A desktop methodology was developed to calculate seasonal water use and water use efficiency at the farm level using the basic water management information and climatic data. The methodology developed in this project will be used in a cotton water management software tool, which is being developed at the ACRI. This software will assist farmers to assess their own water use efficiencies and make comparisons with benchmarks. The methodology developed in this project is also being used by the cotton and grains adaptation program of the Queensland rural water use efficiency initiative (QRWUEI).

A new project proposal has been approved by CRDC for the development of integrated water management strategies for Australian cotton farms using the results and experience gained from this project. The cotton water management software will be developed within this project. Collaboration has been established with QRWUEI staff to trial a developmental version with producers and to provide feed back

A technical summary of any other information developed as a part of the research project including discoveries in methodology, equipment design, etc.

Water flow measurements are necessary to identify water losses in the farm. A number of techniques are available to measure water flows into a farm or paddock. Usually, farmers measure water inputs from rivers and bores using standard meter gauges. However, water inputs to individual fields are not commonly measured due to a lack of equipment and techniques that are simple to use and cost effective.

The measurement of irrigation water at the field level is important for a number of reasons. If the soil moisture deficit is known, it is possible to provide an accurate amount of irrigation water to the crop by measuring water inputs. This will help to minimise drainage and run off losses and to avoid waterlogging conditions. The quantification of irrigation water used for individual fields and for different enterprises in the farm has profound importance in maintaining water accounts and hence good water management. Monitoring and measuring water inputs to individual fields is a key requirement for the calculation of water use efficiencies.

Irrigation siphons provide an immediately available tool to simply measure the amount of water applied to a field. Fundamental flow theories applicable to low pressure pipe systems can be used to calculate the flow rate (discharge in litres per second) from these siphons. If we know the flow rate in the siphons, the quantity of water delivered to a field can be estimated easily. In practice, the relationship between discharge rate and hydraulic head fits the function $Q = Ch^{0.5}$.

Where Q is the rate of discharge (LS^{-1}), h is the head (cm) and C is the calibration constant.

Three different commonly used irrigation siphons: 60mm, 55mm and 50mm external diameters (the internal diameters of the pipes tested were 53.2mm, 48.7mm and 43.8mm) were calibrated to develop a relationship between the water head and discharge. The pipes were approximately 3.5 metres in length. The calibration was done at the hydraulics laboratory of the Charles Sturt University in Wagga Wagga. The discharge co-efficient (C) calculated for 50mm, 55mm and 60mm siphons are 0.55, 0.60 and 0.63 respectively. The details of this calibration and its application is given in the paper titled "Using irrigation siphons to measure in-field water use" attached to this report.

Recommendations on the activities or other steps that may be taken to further develop, dissemiuate, or to exploit the project technology

Monitoring and measuring of irrigation inputs and outputs and maintaining proper records for water management are critical to achieving higher water use efficiencies. A standard method for measuring, recording and analysing is required to make a valid comparison of water use efficiencies between fields and properties. The new CRDC funded project will address the following three major needs.

1. Development of cotton water management software
2. Development of an integrated water management system for the cotton industry
3. Assessing the water use efficiency of cotton production in northern Australia

Development of cotton water management software

With the increased awareness of the importance of water use efficiency within the cotton industry many farmers are keen to assess their own water use efficiencies. However, user friendly tools are not available to the farm office for recording and analysing the water management data. Therefore, it is difficult for managers to make meaningful efficiency estimates for a fair assessment or valid comparison. According to experience gained from this project there is a great demand for a user-friendly water accounting tool for cotton irrigators. User friendly ways of estimating evapotranspiration and calculation of efficiencies at the farm office need to be developed. In collaboration with the CottonLOGIC team, a software tool will be developed to assist producers to analyse their water use efficiencies at field and farm level. The accounting system will provide facilities to farmers to monitor, measure, record and analyse their own water use efficiencies, to compare these with benchmarks and identify ways of increasing efficiency specific to their farms. It will assist farmers to understand the pattern of water use by individual fields and to identify means of saving water and improving water use efficiency specific to the individual fields and farms. The software tool will address the following issues:

- Estimate the amount of water in the on-farm storage
- Estimate the amount of stored soil water in each paddock
- Record water inputs from rivers and bores
- Record quantities of irrigation water used for individual fields
- Estimate and record the amount of on-farm harvested water
- Estimate crop water use using direct (change in soil moisture) and indirect (Modified Penman) methods
- Estimate evaporation, storage and conveyance losses
- Estimate effective rainfall and runoff

The system will be integrated into the CottonLogic software which is already widely used by growers for pest management and record keepiug.

Development of an integrated water management system for the cotton industry

Integrated farm water management means employing all available methods of both utilising rainfall on a farm and scheduling irrigation to reduce irrigation demand and to minimise off-farm movement of water, which may be contaminated with chemicals. The basic components of the water balance (infiltration, run off, soil water storage, evapotranspiration and deep drainage) are clearly closely interrelated and are strongly affected by the land use pattern and farming system. The practical value of cropping sequence, fallow and stubble management in reducing irrigation requirements of subsequent cotton crops will be investigated. Strategies will be developed to conserve soil moisture from pre-season rainfall and modify infiltration characteristics and water holding capacity of the soil by manipulation of the cropping sequence and stubble management.

Most of the cotton growing soils have the capacity to store up to 1.5ML of plant available water per hectare to meet subsequent crop water requirements. This is a significant fraction of the seasonal crop water requirement. By judicious planning of tillage, crop rotation and stubble management, it may be possible to capture pre-season rainfall to increase the stored soil water and improve the infiltration capacity of soils to better utilise rainfall. This will result in reducing the demand for irrigation water. If the irrigation requirement can be reduced by 5%, more than 100,000 ML of water per year can be saved, representing approximately $45 million in potential additional cotton production. The approach may also reduce the risk of off-farm runoff during high intensity rainfall events and hence off-farm contamination.

Assessing the water use efficiency of cotton production in northern Australia.

As part of the newly funded project water nse efficiency of the cotton industry in northern Australia will also be assessed nsing the methodology developed in this project. The objectives will be to identify the current sources of variation in crop water use efficiency (CWUE) between properties, and to benchmark the current water use efficiency in the newly developed cotton farms. The seasonal crop water use (ET), irrigation water used at the farm level, irrigation efficiency, rainfall efficiency and crop water use efficiency will be estimated. The results will help farmers, extension officers and agencies to be aware of the water use patterns, efficiencies and means of improving water use for the cotton industry in the northern regions.

A list of publications arising from the research project

1. **Tennakoon, S.B.**, Milroy,S.P. and Hulugalle,N.R. (1998) Comparison of crop water use efficiency with rotation and continuous cropping in an irrigated vertisol. Proceedings of the 1998 Australian Cotton Conference, Broadbeach, Qld. pp. 537-540.

2. Hickman, M., Rochester, I., **Tennakoon, S.B.**, Hare, C., Hullugalle, N., Charles, G., Allen, S., Nehl, D., Scott, F., Cooper, J. and Conteh, A., (1998) Rotation Crops: What is the impact on an irrigated farming system. Proceedings of the 1998 Australian Cotton Conference, Broadbeach, Qld. pp. 49-59.

3. **Tennakoon, S.B** and Milroy, S.P (1998) Estimation of crop water use efficiency of irrigated cotton farms in the Namoi Valley. Proceedings of the Farming Systems Forum; Australian Cotton Research Institute, 2-3 December 1998.

4. **Tennakoon, S.B** and Milroy, S.P (1999) An assessment of water use efficiency of irrigated cotton in major cotton growing areas in Australia. The Global Changes and Terrestrial Ecosystem (ECTE) conference. University of Reading, UK. 20-23 September 1999.

5. **Tennakoon, S.B** and Milroy, S.P (1999) Estimation of Evapotranspiration in the Cotton Industry. Paper presented at the Cotton Research Development Corporation water balance workshop. Queensland Department of Primary Industries, Toowoomba, 28-29 October 1999.

6. **Tennakoon, S.B** and Milroy, S.P (1999) Quantifying water use efficiency of irrigated cotton farms in northern NSW. The Cotton CRC research conference, 21-22 July 1999.

7. **Tennakoon, S.B** and Milroy, S.P (1999) Using irrigation siphons to measure in-filed water use. The Australian cottongrower magazine, November-December 1999, Vol. 20 No. 6, pp 34-39.

8. **Tennakoon, S.B.** and Milroy.S.P (2000) Evaluation of crop water use efficiency and farm level irrigation efficiency of irrigated cotton farms in northern NSW and southern Queensland. Irrigation Australia 2000 Conference, 23-25 May 2000, Melbourne.

9. **Tennakoon, S.B.,** and S.P.Milroy (2000) Managing water use efficiency on farms, Proceedings of the 2000 Australian Cotton Conference, Brisbane, Qld.

10. **Tennakoon, S.B.,** and S.P.Milroy (2000) Assessment of water use efficiency of irrigated cotton using producer's historical water management data. Australian Agronomy Conference, Australian Society of Agronomy, Horbart Tasmania, Australia.

Appendix i

The use of bales/ML of irrigation water as a performance evaluation index to measure irrigation water saving in the cotton industry.

An accurate evaluation index is required in order to estimate water savings arising from changes made in an irrigation system. One of the conventional ways of evaluating the system is to use the number of bales produced per ML of irrigation water used. This is calculated by considering the amount of lint processed at the gin and the amount of irrigation water released from the dam or the amount of irrigation water pumped from rivers and bores. According to the findings of our project at CSIRO this index is not sufficient to make comparisons between properties or seasons in terms of irrigation water savings arising from the improvements made in the system. Number of bales produced per ML of irrigation water is heavily dependent on the amount of rainfall received during the growing season and the amount of soil reserves used.

The natural rainfall provides a significant amount of the crop water requirement for the cotton farms in eastern Australia. The long-term average growing season (October – April) rainfall varies from 200mm to 500mm with a large variability. The long-term average and the range of annual rainfall for different cotton growing areas are given in table 1.

Table 1. Long-term mean, lowest and highest rainfall (mm) for major cotton growing areas

	No of years	**Mean**	**Lowest**	**Highest**	**Std.Dev.**
Biloela	107	692	295	1157	178
Bourke	117	350	103	856	150
Darling downs (Dalby)	128	676	268	1273	176
Emerald	115	635	205	1406	207
Gwydir valley (Moree)	118	581	201	1108	167
Hillston	113	369	102	712	127
Macquarie valley (Warren)	114	481	152	1213	173
McIntyre valley (Goondi)	119	620	265	1035	169
Namoi valley (Narrabri)	118	641	297	1243	182
Gunnedah	120	616	248	1139	173
St. George	117	517	125	1004	180
Mean		**562**	**206**	**1104**	**171**

This table indicates the variability of rainfall between seasons and valleys. Most of the cotton growing soils contain the capacity to store 0 to 1.5 ML of plant available water and this capacity significantly varies with different soil types.

There is also a considerable variation in evaporative demand between seasons and regions. The irrigation water requirement for cotton is dependent on within season rainfall, stored soil moisture and the evaporative demand. According to the current survey, the irrigation water input could vary from 2ML to 17ML of water per hectare per season. The average irrigation water used and observed efficiency in number of bales per ML of irrigation water is given in the following table.

	96/97			97/98			98/99		
	Pumped ML	Yield bales/ha	bales/ML irrigation	Pumped ML	Yield bales/ha	bales/ML irrigation	Pumped ML	Yield Bales/ha	bales/ML irrigation
Namoi Valley	4.71	**7.71**	1.64	5.16	**8.32**	1.61			
Gwydir Valley	11.86	**7.32**	0.62	12.23	**8.01**	0.66			
Macquarie Valley	7.86	**9.40**	1.20	8.36	**10.50**	1.26			
McIntyre Valley				5.70	**7.84**	1.37	2.18	**7.08**	3.25
Darling Downs				3.13	**7.99**	2.55	2.22	**8.41**	3.79
Emerald				6.30	**7.60**	1.21	3.23	**7.50**	2.32

Because of the high variability in rainfall in eastern Australian irrigated cotton areas, a more appropriate way to measure irrigation water saving from the changes made in the system is to calculate the percentage of irrigation water used to meet crop water requirements compared to the total water inputs at the farm level during the season. We define this as irrigation efficiency with the definition as follows.

Irrigation efficiency

The irrigation efficiency was defined in this project by adding clear spatial and temporal boundary conditions to the definition made by Barrett Purcell and Associates. Total irrigation input is measured at the farm level and it is different from the efficiency of a single irrigation event at the field level. For example if irrigation efficiency of a single irrigation event is 60%, it means that 60% of the water delivered is used through crop evapotranspiration. But most of the other 40% flows to surface and sub-surface areas and the surface runoff is usually captured at the tail end and reused. It is mandatory in NSW to recirculate water within the cotton farm due to environmental concerns. Stopping siphons when water reaches the tail end of the furrow is not a standard practice in every farm. In an irrigation event, the main purpose is to fill the profile completely. Depending on the infiltration capacity and saturated hydraulic conductivity the time taken to fill the profile varies with different soils. Some cotton farmers let water flow for a long period along the furrows in order to fill the soil profile completely. In this kind of system they collect the tail end water and send it back to the storage for future use. Multiple use cycle systems are systems where some proportion of seepage, operational spillage and runoff from the tail end, which are often thought of as losses can be reused in the same farm or another part of the command area. For such systems, because of multiple reuse the supply of water to the farm can be less than the total (aggregate) amount of water actually applied to crops in successive irrigations. Because of this water multiplier effect the whole farm efficiency is higher than the efficiency of individual use-cycles. Some old measurements of efficiencies were not meant to measure total water utilisation. But they have often been misapplied and used for evaluating field or micro level irrigation performance in the context of farm or regional basis evaluations.

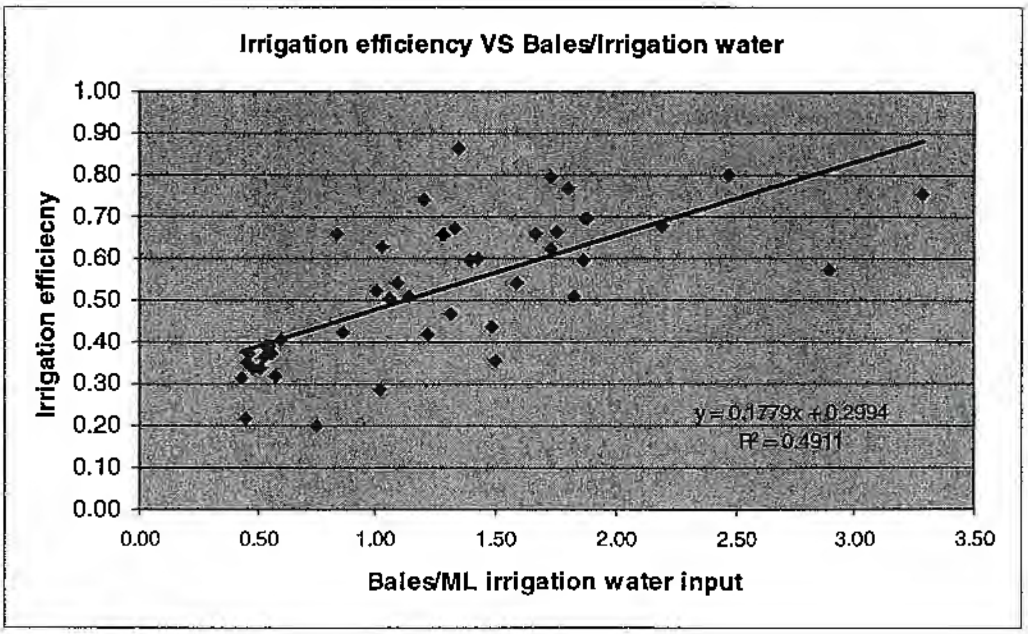
In NSW farmers are not allowed to discharge the runoff therefore it is captured at the tail end and stored for future use. The harvested water will be used as a part of irrigation water and can be counted as an irrigation component in calculating irrigation efficiency. Therefore, in cotton farms the irrigation efficiency can be best defined as follows.

$$IE = \frac{CropET - RF_E - SM_D}{\text{Total water pumped from rivers and bores + harvested water}}$$

CropET - Total evapotranspiration, **RF_E** - Effective precipitation, **SM_D** - Soil moisture depletion

The calculation of crop ET, effective precipitation and soil moisture depletion can be estimated fairly accurately using direct measurements and water balance models. These can be measured or estimated at the field level and averages can be calculated at the farm level. The harvested water can be approximately estimated by measuring the water level at the storage before and after a storm.

The index bales/ML of irrigation water is dependent on the amount of irrigation water used and the yield obtained. The amount of irrigation water used is largely depends on in-season rainfall. The irrigation efficiency mainly depends on conveyance, storage and application efficiencies. The relationship between irrigation efficiency and bales per ML of irrigation water observed from commercial farms for the last two seasons is given in the following graph.



Even though irrigation efficiency and bales per ML has a positive relationship, less than 50% (R-squared is 0.49) of the variability in irrigation efficiency can be explained from the bales/ML index. This result clearly indicates that the bales/ML irrigation water index can not be used as a measure of irrigation efficiency.

The irrigation efficiency calculated in this project is the combination of storage, conveyance, distributiou and application efficiencies at the farm level for the whole growiug season. This index is an appropriate index to evaluate the system in terms of water savings. It clearly indicates the losses occurring in the system due to management and irrigation hardware settings in the farm. This parameter does not heavily depend on rainfall or evaporative demand. It is simple and is an absolute index, which can be used to compare between properties, regions or seasons. For example 60% irrigation efficiency means that 40% has been lost within the farm. Improving 60% to 70% mean that 10% of water losses were prevented. Using this figure it is possible to calculate the amount of water saved over a period of time.

Papers produced from this project

Proceedings of the 1998 Australian Cotton Conference, Broadbeach, Qld. pp. 537-540.

Comparison of crop water use efficiency with rotation and continuous cropping in an irrigated vertisol

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Water use efficiency is a key issue for the Australian cotton industry. For the individual producer the focus is to maximise returns from a limited resource. However, the current debate on allocation of water between domestic, agricultural and environmental sectors, imposes additional significance to water use efficiency at the industry level. We are conducting a project that focuses on crop water use efficiency as a component of whole farm water nse efficiency. This will be achieved by (i) identifying the current sources of variation in crop water use efficiency between production units and (ii) quantifying the contribution of rotation and tillage practices to the water use efficiency of irrigated or partially irrigated cotton crops. The aims are three folds:

1. To provide benchmarks which producers can use to identify the strengths and weaknesses in their own operation.
2. To identify crop management practices currently used in commercial operations associated with high crop water use efficiency.
3. To provide an assessment of the current performance of the industry as a whole as a measure against which progress can be identified.

Here we present some preliminary results on the effects of rotation options on the water use efficiency of subsequent cotton crops. Data from a long-term crop rotation trial conducted at the Australian Cotton Research Institute (ACRI) were analysed to find the effect of crop rotation and tillage systems on water use efficiency of the cotton crop. This experiment was established in 1985 and the details of this experiment are given elsewhere (Constable *et al.*, 1992). There were three major treatments between 1985 to 1993, which were (a) intensive tillage with cotton sown in October every year (b) minimum tillage with cotton sown in October every year and (c) a cotton/winter-wheat/summer-fallow sequence where cotton was sown with minimum tillage in October and wheat with no-tillage in May. Details of these treatments and land management practices are given in Hulugalle and Entwistle (1996). Since 1993 the rotation treatment (c) has been changed to minimum tillage continuous cotton. This provides us with an opportunity to test the persistence of rotational effects for a longer period.

Crop water use efficiency (CWUE) was calculated as the ratio of the lint yield of the crop to the amount of water used by the crop in transpiration and evaporation (evapotranspiration, ET). That is the amount of yield (lint) per unit of water actually used by the crop during the growing season;

Crop water use efficiency (kg/mm/ha) = lint yield (kg/ha) / ET (mm)

The yield/ET ratio considers only the water that was used as transpiration and evaporation and does not consider the total amount of water applied or pumped from the river, storage or bores. These measures introduce the engineering aspects of whole farm water use efficiency and are being examined in a complementary project conducted by the University of Southern Queensland.

The calculation of CWUE required the estimation of the actual amounts of crop water used during the growing season (ET). In this experiment, neutron probes were used to measure soil moisture content to 1.2 meters at intervals during the growing season in all treatments. This information was available only for the 93-94, 94-95 and 95-96 seasons. However, these readings are not sufficient to estimate the seasonal water use by the cotton crop, because they do not account for all the water used by the crop. To improve the accuracy of the estimation of water use by the crop, a spreadsheet was developed that calculates the total ET for the season using the values obtained from the neutron probes. Gaps in the records were filled using a soil water balance model, which simulates the water content of the soil profile on a daily basis based on climatic data and irrigations.

Differences in crop water use efficiency

The beneficial effects of crop rotation (cotton/winter-wheat/summer-fallow) on CWUE persisted for one year after this treatment was discontinued. In the 93/94 season, which was the first year after the rotation treatment ceased, crop water use efficiencies were significantly different ($P<0.05$) between treatments (Fig. 1). The minimum tillage rotation treatment had the highest CWUE of 1.03 bales/ML. The lowest CWUE of 0.76 bales/ML was obtained for the maximum tillage continuous cotton treatment. However, in the second and third year after the rotation treatment was stopped, the CWUE was not significantly different. This may be due to the disappearance of the rotational effect with time. It can be observed that the differences of CWUE values between treatments are declining with time.

While there were differences in CWUE between the treatments it is important to note that these did not result from differences in total water use but from the yield advantage conferred by the rotation treatment. The total water use (ET) for the three treatments did not differ significantly in any year (Table 1).

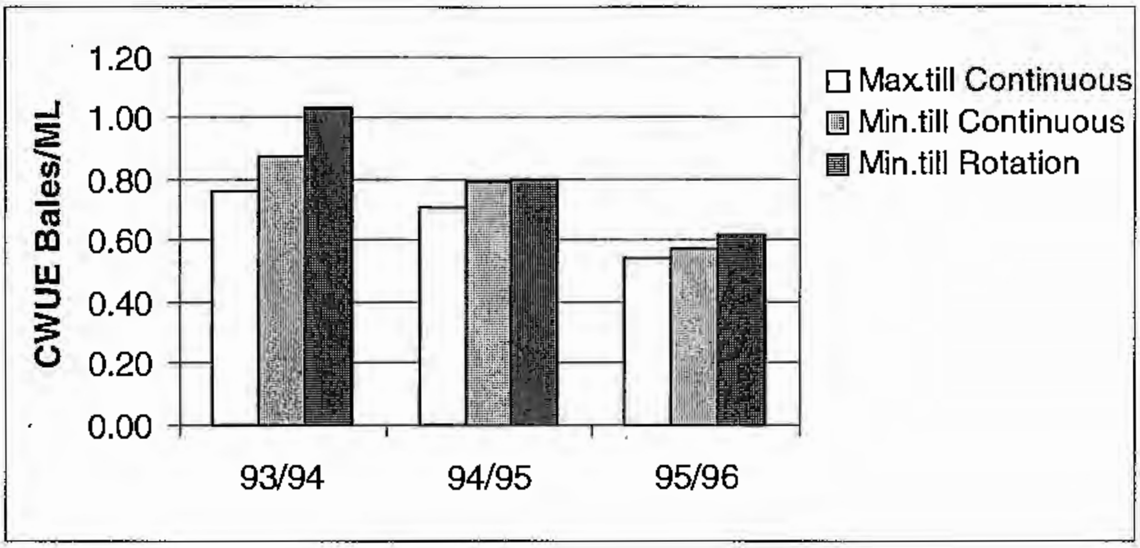

Fig 1. Crop water use efficiencies for the three seasons

Table 1 Yield, total water use and CWUE for the seasons

Treatments	93/94			94/95			95/96		
	Yield B/ha	**ET mm**	**CWUE B/ML**	**Yield B/ha**	**ET mm**	**CWUE B/ML**	**Yield B/ha**	**ET mm**	**CWUE B/ML**
Max.till. Continuous	5.7	750	.76	5.3	747	.71	4.3	782	.55
Min.till. continuous	6.6	757	.87	5.9	746	.79	4.5	797	.57
Min.till. rotation	7.6	733	1.03	6.3	786	.80	4.9	788	.62

Seasonal water use

The water used during the growing season from different sources; irrigation, rainfall and soil reserves were separately estimated (Table 2). The mean total seasonal water use for the three seasons was 746 mm, 760 mm and 789 mm for 93/94, 94/95 and 95/96 respectively. As expected, the proportion of the total water use that was contributed by irrigation varied dramatically from season to season depending on the amount of rainfall received during the season and the available soil reserves. However in any given year, the proportion of water used from irrigation did not vary between the treatments. Even though there were differences in CWUE between the treatments, this was not reflected in a difference in either total water use, or in the amount of water required from irrigation during crop growth.

Table 2. Proportion of crop water use derived from different sources for the different management treatments.

Season	Treatment	Rainfall	Irrigation	Soil reserves
93/94	max.till.cont.	0.36	0.37	0.27
	min.till.cont.	0.36	0.36	0.28
	min.till.rot.	0.37	0.35	0.28
94/95	max.till.cont.	0.37	0.48	0.15
	min.till.cont.	0.37	0.47	0.16
	min.till.rot.	0.35	0.50	0.15
95/96	max.till.cont.	0.58	0.12	0.30
	min.till.cont.	0.57	0.11	0.32
	min.till.rot.	0.58	0.11	0.31

Conclusion

These first results indicate that the rotation of cotton-wheat-fallow had beneficial effects on cotton water use efficiency when compared to continuous cropping. However it is important to note that this advantage was derived from the yield advantage conferred by the rotation and not from differences in water use.

The next stage of this project will include the analysis of the CRC farming system trials and other long-term rotation trials to continue investigating the effects of rotations on crop water use efficiency. We will also collect on-farm water management information from producers, which will be processed using approaches similar to those presented here. The aim will be to evaluate the current level of crop water use efficiency of the cotton industry.

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Estimation of Evapotranspiration in the Cotton Industry

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Evapotranspiration (ET) is a measure of the actual amount of water used by growing plants and crops. It combines evaporation and transpiration. Evaporation is the water evaporating from the adjacent soil, water surfaces, or from the surface of leaves of plants. Transpiration is the loss of water from plants in the form of vapour and can be regarded as the dominant process in plant water relation. Transpiration involves two stages: (a) the evaporation of water from cell walls and (b) its diffusion out of the leaves, mainly through the stomata. This process is driven by a constant inflow of energy. The transpiration process is essential not only in providing an inflow of nutrients to the plant but also to keep the plants cool. Kramer (1983) has explained the mechanisms of transpiration. The relationship between evapotranspiration and crop yield for various crops is given in (Stewart and Nielsen 1990; Doorenbos and Kassam 1979). Different plants have different water requirements and thus cause different ET rates. The estimation of crop water use (ET) is the key requirement for irrigation management. CROPWAT (Smith 1992) and ENWATBAL (Van Bavel and Lascanso 1987) are examples of irrigation management computer programs which calculate crop transpiration and evaporation from meteorological data. A summary of commonly used methods of evapotranspiration estimation is given below.

<u>Estimation of evapotranspiration</u>

Evapotranspiration can be determined by a number of methods. The Food and Agriculture Organisation of the United Nations (FAO) has a number of publications regarding the estimation of crop water requirements and irrigation management. FAO irrigation and drainage paper No. 24 by Doorenbos and Pruitt (1977) has become the widely accepted international standard publication for the estimation of evapotranspiration for irrigation management. The latest FAO publication (No. 56) explains guidelines for crop water requirements.

Indirect Measurement Methods

The methods of evapotranspiration estimation falls into three general categories, the direct and indirect methods and the simulation of the soil water balance models. Indirect methods of measuring ET are basically done by the theoretical and empirical methods. Brutsaert (1982) provided a detailed explanation of the history of evaporation research and various meteorological approaches including the limitations of different approaches. Most of the indirect methods estimate evapotranspiration using meteorological data.

Potential Evapotranspiration

Since there are thousands of cultivated plants, scientists have tried to simplify matters by establishing a standard ET rate for general reference and use. The standard is referred to as potential evapotranspiration. Potential evapotranspiration is an estimate of the water requirements of a 4-inch grass growing in a deep soil under well-watered conditions. The technical term for this is the "Potential Evapotranspiration of a grass reference crop" or

"PET". PET depends on the climate and varies from location to location. Special weather stations are used to collect the climatic data for calculating PET, including temperature, dew point temperature (relative humidity), wind speed, and solar radiation. The water requirements of specific crops (ET_a) can be calculated as a fraction of the PET. This "fraction" is called the crop coefficient (K_c). Crop coefficients vary depending on the type of plant and its stage of growth. These crop coefficients can be derived from experimental data.

$ET_a = K_c * PET$

Actual evapotranspiration ET_a is the amount of water lost from the plant and soil to the atmosphere given the current meteorological conditions, soil water availability and plant growth.

Estimation of Potential Evapotranspiration

Doorenbos and Pruitt (1977) explained four methods to estimate PET depending on the available climatic data.

1. *Blaney-Criddle:* uses only mean daily temperature, and introduces correction factors based on estimates of humidity, sunshine and wind.

2. *Radiation method:* estimates PET based on measured solar radiation and temperature, with correction factors based on estimates of wind and humidity.

3. *Penman method:* This method requires daily maximum and minimum temperature, humidity, wind and sunshine duration or radiation.

4. *Pan evaporation method:* Pan evaporation is related to PET by an empirically derived coefficient (K_p).

Some other methods of estimating potential evaporation are Penman-Monteith (Monteith, 1965), Hargreaves and Samani (1982), and Priestley and Taylor (1972). The Penman-Monteith method requires solar radiation, air temperature, wind speed, and relative humidity. The Priestley-Taylor method requires solar radiation and air temperature as inputs, while the Hargreaves method requires air temperature only. Scotter et al (1979) found that the Priestley-Taylor method was as accurate as the Penman method or the Class A pan data from an experiment conducted for pastures. However for a row crop during incomplete cover the Priestley-Taylor method did not provide accurate estimates (Tanner and Jury 1996).

Ritchie (1972) estimated potential soil water evaporation as a function of potential evaporation and leaf area index (LAI, area of plant leaves relative to the soil surface area). Actual soil water evaporation was estimated by using exponential functions of soil depth and water content. Plant water evaporation can be estimated as a linear function of potential evaporation and leaf area index.

Bowen (1926) proposed the use of the ratio of sensible and latent heat fluxes to facilitate the determination of evapotranspiration (energy balance method). Bowen's ratio method uses temperature and actual vapour pressure to estimate evapotranspiration. Net radiation (Rn) and the soil flux (G) can be measured directly, but it is more difficult to measure H (sensible heat exchange), Bowen proposed the use of the ratio of sensible and latent heat fluxes to facilitate the determination of Et. Bowen's ratio (β) uses temperature and actual vapour pressure.

β= H/LEt
= 0.66 (T1-T2) / (e1-e2)
T = temperature at the crop canopy (T1) and 1m above canopy (T2)
e = vapour pressure at crop canopy (e1) and 1m above canopy(e2)

By substituting the Bowen Ratio into the energy balance equation, it can be rearranged and solved for Et.

$$Et = (Rn-G)/[L(1+\beta)]$$

Prueger et al (1997) compared the Bowen ratio method with the lysimeter method and found that the Bowen ratio values agreed to within 10% of the lysimeter readings throughout the season. Faulkner (1992) also found that the Bowen ratio provides a convenient, portable and accurate means of estimating evapotranspiration from crops.

Evaporation pans: This was the first evaporation measurement instrument used by scientists back in the 17^{th} Century. It allows the measurement of the direct loss of water through evaporation from a free water surface. Now, the US class A pan has become the international standard device to measure evaporation. The class A pan is 1210 mm in diameter, 225 mm deep and the pan should be filled to a maximum depth of 205 mm and the water level should remain above 180 mm in depth. The pan coefficient (k_p) should be used to correct the pan evaporation to the reference crop. A pan coefficient should be corrected to suit the environment conditions (Doorenbos and Pruitt, 1977).

Infrared Thermometers: The infrared thermometer can be used to estimate the crop evapotranspiration. Details of this method are given in Ben-Asher et al (1989). This technique involves taking non contact temperature measurements from the crop canopy. The canopy temperatures and climatic data can be used to estimate evapotranspiration (Kjelgaard et al 1996). A canopy temperature energy balance model was compared with other methods to estimate ET for short periods by Kjelgaard et al (1994).

Remote sensing: One of the applications of remotely sensed surface temperature is to determine the latent heat flux (LE) or evapotranspiration (ET) from field to regional scale. A common approach has been to use surface-air temperature differences in a bulk resistance equation for estimating sensible heat flux, H, and to subsequently solve for LE as a residual in the one-dimensional energy balance equation (Kustas, 1990). A model has been developed to use instantaneous remotely sensed multispectral data for regional evapotranspiration (ET) assessment with the help of ground-based meteorological data (Brown and Owen-Joyce 1991). Estimation of crop evapotranspiration using optical and microwave remotely sensed data has been done by Vidal et al (1996). The data from an automatic weather station was used to estimate potential evaporation from a formula based on incoming solar radiation estimated from visible band data obtained by the GOES satellite and climatological values of temperature (Stewart et al 1999).

Direct measurement methods

Lysimeters: Lysimeters can be used for direct measurement of evapotranspiration. The depth and size of the Lysimeters are dependent on the intended purpose of the study. Lysimeters provide accurate and sensitive measurements of ET if they are properly maintained. Lysimeters are routinely used to develop crop coefficients for crops grown in well-drained soils. Simultaneous monitoring of the crop and grass Lysimeters help to derive the crop coefficient for various cycles of the season or even hourly if necessary.

Sap flow measurements: Measurement of velocity of water flow in the xylem of plants can be used to estimate transpiration. Instruments have been developed to measure heat pulse tracers in plants and trees which is directly related to sap flow. The probe works by sending a regular pulse of heat directly into the sapwood (xylem). Two sensors detect temperature both just below (usually 5 or 6 mm) and above (10 or 12 mm) the heater probes. The xylem temperature at either sensor is directly related to the distance from the heater and sap velocity. This technique is usually used to measure transpiration of trees. Sap flow measurements have been used to estimate transpiration from cotton in Arizona by Dugas et al (1994).

Soil water balance method: Evapotranspiration can be inferred from the residual of the soil water balance after all other terms have been measured thus;

$$ET=SW+P+I-D-R$$

SW= moisture in soil, P= precipitation, I= irrigation, D= deep drainage, R= run off

This method has been successfully used in a number of hydrologic-scale studies where entire drainage basins have been studied. In small field studies, this method has been used to determine the soil water use by crops for short periods. The soil water balance as described above requires accurate measurement of all parameters. A number of techniques and types of equipment are available for the accurate measurement of soil moisture. Aydin (1994) estimated values of evaporation, drainage rates and water withdrawal by roots from field data based on water flow equations. Most of the commercial cotton growers in Australia use direct soil moisture measurement for irrigation scheduling. However the spatial variability of soil water content has to be considered in estimating evapotranspiration from soil moisture data (Bertuzzi et al 1994).

Comparison of different methods of ET estimation have been made by many scientists all over the world. Howell et al (1997) found that the Penman-Montieth equation was better than the combination, radiation and temperature based methods in estimating daily ET rates for wheat, sorghum and corn. Mahrer and Rytwo (1991) compared the Bowen ratio method, Penman equation and Class A pan for estimation of evapotranspiration and their results showed that evapotranspiration rates were strongly affected by the intensity and arrival time of sea breezes. Crop evapotranspiration in wheat, soybeans and cotton were compared with estimates derived from measured potential evapotranspiration from the grass crop and crop coefficients calculated by the FAO method by Mantovani et al (1992). They found that the Penman-Monteith method substantially underestimated ET for high evaporative demand periods in Spain.

Estimation of evapotranspiration of cotton in Australia

The cotton industry is relatively new in Australia and 80% of the Australian cotton is grown under irrigation. The seasonal evapotranspiration of the cotton crop varies from 500 mm to 950 mm and in most of the places rainfall is supplemented by irrigation. The history of calculations and estimations of evapotranspiration in Australia has been explained by Fleming (1998).

Estimation of cotton evapotranspiration by Peter Cull

Peter Cull (1979) used the computer based soil water balance model by Ritchie (1972) to estimate the crop water requirement of the cotton crop in the Namoi Valley. The model parameters and values particular to the cotton crop in the Namoi valley were derived and validated from field studies. The results of this study were also presented in Cull et al (1981). He also used the Priestly and Taylor (1972) energy balance technique to estimate potential evapotranspiration.

$E_t = \lambda * R_n * \nabla/(\nabla+Y)$

E_t = Potential evaporation, mm/day, R_n - Net radiation above the canopy

∇ = Slope of the saturation vapour pressure curve at air temperature

Y = Psychrometric constant, λ - Empirical constant

Net radiation was calculated from the measurements of solar radiation using the Ritchie (1971) model. This involves estimation of crop albedo. The plant transpiration was calculated from the relationship of plant transpiration to potential evapotranspiration (Ep/Et). This relationship is dependent on the leaf area index (LAI) and the following equations were used.

$Ep/Et = 0.495\ (LAI)^{0.5}$ for $0 < LAI < 3$

$Ep/Et = 1.0$ when $LAI > 3$

Soil evaporation was considered in two stages, the constant rate stage and the falling rate stage. For the constant rate stage, Cull estimated the "U" value (the amount of water freely evaporating from the soil surface) from field experiments to be 14.0 mm. When the soil is freely evaporating in stage 1 the potential evaporation rate below the canopy at the soil surface was calculated using the same manner as the potential evapotranspiration.

$Eso = \lambda * R_n * \nabla/(\nabla+Y)$

The stage 2 evaporation has been calculated using the following relationship

$\sum E_s = \alpha\ t^{-0.5}$

Cull estimated the α value as 7.83 mm day $^{-1}$

According to Cull plant transpiration was affected by soil water status after a critical level of soil water extraction had occurred. This critical lower level for potential evapotranspiration was assumed to be 30% by volume of the extractable soil water.

Cotton ET estimation in SIRATAC

Constable et al (1983) used the Ritchie water balance model with the Priestly-Taylor modification of the surface energy balance to estimate crop evapotranspiration in the

SIRATAC model. Climatic inputs required to run this model are rainfall, solar radiation and maximum and minimum temperatures. Pan evaporation figures were used when solar radiation was not available.

Calibration of the water balance model for cotton in the Namoi Valley, NSW (un published information).

In the early 90's G.D. da Roza, A.B Hearn and P.M Fleming found that the aerodynamic component of the Penman combination equation derived from the standard climatological observations was not adequate to estimate evapotranspiration from a well-watered cotton crop in the Namoi valley. They also found that Priestley-Taylor coefficient was unlikely to be satisfactory. They derived locally based aerodynamic terms for the combination equation to estimate of evapotranspiration. They concluded that the calibrated empirical functions for the advection component of the evapotranspiration formula are essential for accurate simulation of the soil water balance. The advection term (AT) was determined by the difference between measured evapotranspiration (E_t) and estimated equilibrium evaporation (E_a). The relationships they found are as follows. They recommend the Penman method to estimate evapotranspiration if the data are available.

AT= 0.010 (1.0 + 0.0248 u) (e*a-ea) (Y/D+Y)
AT = 1.420 + 0.070 T
AT = 0.940 + 0.012 (e*a-ea) + 0.040 T

T = mean temperature in degree Celsius
e*a = saturated vapour pressure at mean air temperature
ea = actual air water vapour pressure
Y = the psychrometric constant
D = the slope of the vapour pressure temperature curve for water at mean air temperature.

Mateos and Hearn (1991) continued the calibration of the water balance model for cotton in the Namoi Valley. They partitioned the Ritchie (1972) water balance model for evapotranspiration between plant and soil. In the Ritchie model soil evaporation is calculated in two stages. The function for stage 2 (falling rate stage) soil evaporation is

$$E_s = \alpha\, t^{-0.5} - \alpha\,(t-1)^{-0.5}$$

Mateos and Hearn (1991) estimated the mean value of α to be 4.3 and 3.2 mm day $^{0.5}$ for LAI 0.6 and 2.0 respectively. These figures are different from Cull's α value. They also modified the plant evaporation function as follows.

$Ep/Eo = 1 - e^{-0.52LAI}$ LAI < 1.6
$EP/Eo = 0.008 + 0.31\ LAI$ 1.6 < LAI < 3
$EP/Eo = 1$ LAI > 3

A comparison of the methodologies for predicting crop evaporation under field conditions (Shane Kable)

Kable (1996) compared the energy balance method, modified Penman method and evaporation pan measurements for predicting crop evaporation under field conditions for his Graduate Diploma in Natural Resources at the University of New England. The trial sites were a pasture site in Armidale and a cotton site at the Myall Vale Australian Cotton Research Institute. He used the standard Class A pan data in this comparison. The Penman (1948), modified Penman equation (Doorenbos and Pruitt 1977) and Bowen ratio energy balance model (Bowen 1926) were also used in this comparison. In this study, the class A pan data were obtained from the nearest meteorological stations. Data required for the Penman based calculation were collected from the ACRI meteorological station. The required information for the energy balance model was collected from the experimental sites. Results from both sites showed that there was a significant difference between the energy balance and both the Penman and pan methods. He concluded that the Penman and pan methods are not suitable for daily ET prediction with his method of data collection.

Evapotranspiration estimation comparison by Janelle Montgomery

Janelle Montgomery compared the energy balance model, Penman method and class A pan method to estimate evapotranspiration. The comparison was done at the Australian Cotton Research Institute, Narrabri with grey clay soils and at AUSCOTT in the Gwydir valley with grey clay soils and red alluvial soils. She used the direct reading ET assessment monitor based on climatic measurements concerned with energy balance equation to estimate evapotranspiration. Actual evapotranspiration was measured using a suit of instruments that record different climatic measurements concerned with the energy balance equation.

$$Rn = H + LEt + G$$

Rn = net radiation, G = heat flux into the soil
L = latent heat of vaporisation (48.5 cal cm-2), Et = evapotranspiration
H = sensible heat exchange

Direct Reading Evapotranspiration Assessment Monitor (DREAM) has been used to collect this data. The measurements recorded using the DREAM system include:

1. Rn (MJ m^{-2}), measured directly using a net radiometer situated above the crop canopy
2. G, measured directly using a soil heat flux plate which is placed 5 mm beneath the soil surface
3. Temperature within and above the crop canopy (T1 and T2)
4. Humidity within and above the crop canopy (RH1 and RH2) are measured directly with two pairs of aspirated wet and dry bulb platinum resistance thermometers. The lower pair situated just above the crop canopy and the upper pair 1.3m higher to obtain a temperature difference greater than 0.2°C. Temperature and humidity are required to calculate actual vapour pressure for Bowen's Ratio. The temperature and vapour pressure gradients are also used directly in Bowen's ratio.

The actual vapour pressure at each height (e1 and e2) has been calculated using the following equation:

$$e = e_s * RH$$

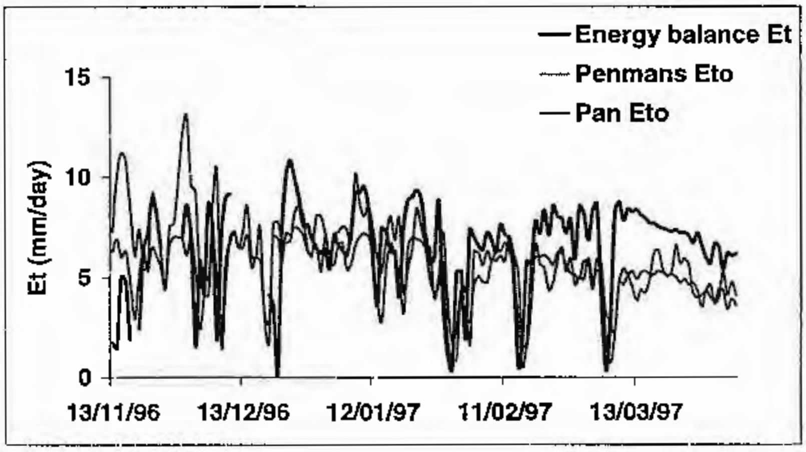
e = actual vapour pressure, e_s = saturated vapour pressure, RH = relative humidity
Saturated vapour pressure changes with air temperature and was calculated using the following function:

$$y = 6.5495e^{0.0621x}$$

y = saturated vapour pressure, x = air temperature

The actual evapotranspiration measured throughout the cotton season is shown in figure 1. The variability in Et was consistent with the weather conditions experienced over the season. The large drops in Et were during wet weather. Janelle concluded that the pattern in Et over the season is similar between each method and actual values differ due to differences in the parameters used to calculate Et. For example the energy balance method takes into account the effects of advection whereas Penman method does not, thereby, underestimating Et. Also the energy balance uses data collected every thirty seconds giving an integrated value for the day, whereas Penman and pan are generally based on one recording per day. In a similar situation Faulkner et al (1998) measured evapotranspiration from direct measurements based on the energy balance model and reported that the FAO modified Penman equation over-estimate evapotranspiration by more than 20%.

Figure 1. Evapotranspiration comparison at Auscott (Red Alluvial)



Estimation of seasonal ET for the cotton water use efficiency project at the CSIRO Cotton research unit at Narrabri.

The objective of this project is to evaluate water use efficiency of the cotton industry and to identify sources of variations in water use efficiency. Estimation of seasonal evapotranspiration is one of the major prerequisites for calculating crop water use efficiency. Historical soil moisture information and meteorological data collected from commercial producers were used to estimate seasonal ET. However, in most of cases, the water content of the soil profile has been measured at irregular intervals and these readings by themselves are not sufficient to estimate the seasonal water use by the cotton crop. With the probe readings it is also not possible to partition the water use to different components such as transpiration and soil evaporation. Therefore, a modified Ritchie (1972) soil water balance model was used to simulate the water content of the soil profile for days when measured values are not available.

A spread sheet model was developed using EXCEL to estimate the soil water balance in a cotton field on a daily basis by combining observed neutron probe soil moisture data with simulated daily evapotranspiration (ET). The probe readings were used when probe readings were available to allow a direct calculation of water use and simulated values were used for missing values. The water balance was calculated using the following equation. In this water balance model deep drainage losses are considered negligible (Douglas 1997).

$$SMC = Pre.SMC + ER + I - ET$$

SMC = soil moisture content in mm, **Pre.SMC** = SMC of the previous day
ER = effective rainfall mm, **I** = amount of irrigation intake in mm
ET = daily evapotranspiration

Estimation of ET

The modified Ritchie model was used to estimate the daily evapotranspiration. This model estimates crop transpiration and soil evaporation separately. The transpiration rate is dependent on the potential evapotranspiration and the leaf area index. The required climatic information is daily rainfall, daily maximum and minimum temperatures, wet bulb temperature, solar radiation and sunshine hours. This information was obtained from the CRC web site and on farm daily rainfall figures were also used. The values of daily LAI is also calculated using a standard LAI index curve developed at the ACRI. Potential evaporation is calculated using the following equation.

$E_p = \lambda * R_n * \nabla/(\nabla+Y)$
E_p - Potential evapotranspiration, mm/day
R_n - Net radiation above the canopy
∇ - Slope of the saturation vapour pressure curve at air temperature
Y - Psychrometric constant
λ - Empirical constant (1.08)

The net radiation was calculated by measuring solar radiation using the following empirical relationship.

$R_n = 0.76 * (1-\beta) * R_s - 0.14$
R_n - net radiation, cal cm^2 min$^{-1,}$ R_s - solar radiation, cal cm^2 min$^{-1,}$
β - crop albedo

Crop albedo is calculated using the leaf area index (LAI) and is used for converting daily solar radiation on the basis of canopy development.

$\beta = \beta_s + .025 * (0.23 - \beta_s)$ LAI
Where β_s of 0.095 is the average albedo of a bare soil (Ritchie, 1971)

The value of ∇ is calculated using the following equation, which is used in the OZCOT model.

$\nabla = (\exp(21.255\text{-}5304/TK))*(5304/TK^2)$
TK is the mean temperature in Kelvin (mean temperature in Celsius + 273)

Y = 6.6E-04*P*(1.0+0.00115*TEMPWET)
P = 1013 – 0.105 * elevation in meters
TEMPWET = wet bulb temperature

Actual transpiration (Et) is calculated from the relationship of plant transpiration to potential evapotranspiration using the LAI. The following equation is used to calculate the actual transpiration.

$E_p/E_t = 0.495 \text{ LAI}^{0.5}$

Soil evaporation losses occur in two stages, the constant stage and the falling rate stage.

Stage 1 (constant) soil evaporation

When the soil surface is wet water evaporates freely from the surface. The rate of evaporation can be calculated in the same manner as the potential evaporation. However, after loosing a certain amount of water from the soil the rate of evaporation changes. This amount of rapid evaporation from the soil is a characteristic of a soil and is often symbolised as "U" value. The "U" value for Namoi valley is estimated by (Cull, 1979) as 14.0 mm. The rate of stage 1 soil evaporation is calculated using the following equation (Ritchie, 1972).

$$ES_1 = R_n \; * \; \nabla/(\nabla+Y) * e^{(-0.4\,LAI)}$$

Stage 2 (falling) soil evaporation

During the falling rate evaporation the soil evaporation rate is dependent on the hydraulic properties of the soil and is less dependent on the available energy. Cumulative evaporative losses from the soil can be estimated by the following equation (Ritchie, 1972).

$$\Sigma ES_2 = \alpha \; t^{-0.5}$$

Where α is a parameter depending on soils hydraulic properties, t is time in dates from the onset of the falling rate stage. Different α values have been found by (Cull, 1979) and (Mateos and Hearn, 1991) and these values were evaluated for the estimation of crop water use. Cull's α value is 7.83 mm per day. Mateos and Hearn have suggested a variable value with LAI; 4.3 and 3.2 mm per day for LAI 0.6 and 2.0 respectively. These values of α were evaluated for the estimation of cotton crop water use and Peter Cull's modified α value was found to be more accurate in estimating ET.

In estimating the soil moisture profile, it was assumed that the soil moisture content at sowing (starting date) was equal to the maximum water holding capacity (WHC) of the soil. The WHC of the soil was estimated from the observed soil moisture content. It was also assumed that the soil could absorb water from a rainfall or an irrigation event until its maximum water holding capacity was reached with the rest of the water leaving the system as run-off and being harvested for future use. The amount of water infiltrated into the soil was calculated by taking the difference between maximum WHC and moisture content prior to rainfall or irrigation. Due to the low saturated hydraulic conductivity of the soils in the Namoi Valley, lateral, upward and downward (deep percolation) water movements have been considered as negligible.

In order to improve the accuracy of the simulation process, whenever the observed values were available the simulated value was replaced by the observed value and simulation continued from that point until the next observed value was met. An example of simulated soil moisture contents and the observed soil moisture contents were plotted and is given in Fig. 1.

The model computes water use in different components and estimates the amount of transpiration and soil evaporation separately. It also calculates the amounts of irrigation, rainfall and soil reserves used by the crop during the growing season. The separate estimation of irrigation water and rainwater used by the crop is important to calculate the irrigation efficiency and the effectiveness of rainfall. The used soil reserves are calculated by subtracting the soil moisture content at harvest/defoliation from the soil moisture content at sowing. A sample model output is given in Table 1.

The crop water use (ET) during the growing season from different sources; irrigation, rainfall and soil reserves have been separately estimated. It should be noted that the total percentage of water used in table 1 is not equal to 100 because of the adjustments made when the simulated value was reset to the observed values). This is the fraction of moisture that can not be explained due to the differences between the model estimations and measured values. However, close estimations have been made as it is difficult to separate the total water used into different components exactly.

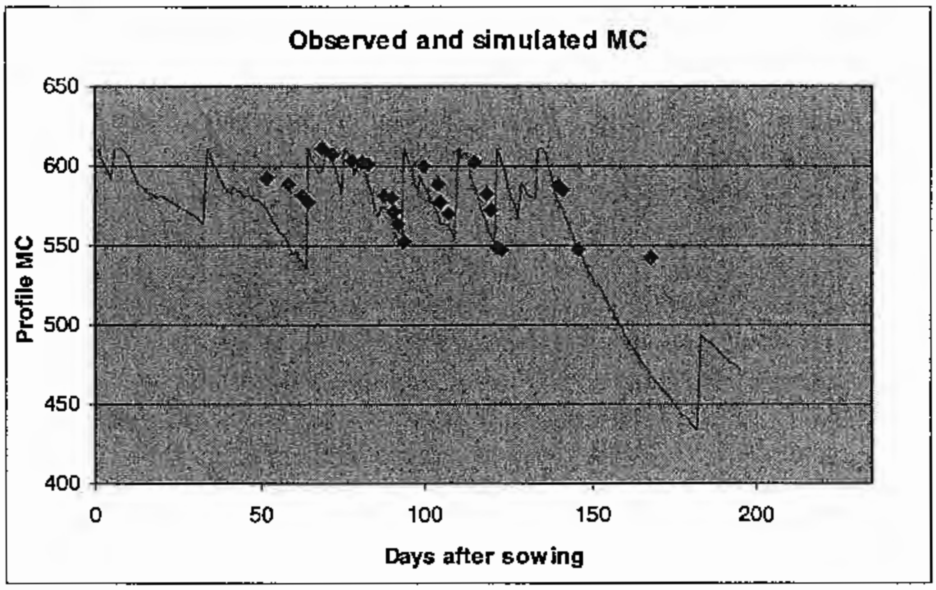


Fig 1. Simulated and observed moisture content (not adjusted). Dots are observed values and the line is estimated moisture content.

Conclusion

Evapotranspiration can be estimated by a variety of methods depending on the availability of data, type of equipment and technology. Most of the indirect methods of ET estimation use meteorological data to estimate potential evapotranspiration. These methods have been tested and compared with each other by many scientists all over the world. Most of the results of these tests and comparisons are site and time specific. This is mainly due to the use of various methods and techniques of measuring meteorological data and the variations in soils and ecosystems.

The method of ET estimation is also dependent on the scale of the system. In the past, met data were used to estimate ET or crop water requirements at farm or paddock level. The use of correct crop coefficients is very important for the accurate estimation of crop water use. However, with the development of technologies, the direct and accurate measurement of ET via soil moisture content is possible for the purpose of assessing crop water requirements at the farm or paddock level. The direct measurement of soil moisture status in the paddock is common in the Australian cotton industry. For example ENVIROSCAN can estimate change of soil moisture on a minute by minute basis and it can be graphically viewed on the computer screen. Crop water use, water deficits in the soil, effectiveness of rainfall and irrigation requirements can also be easily estimated by using this equipment. Infrared thermometers provide instantaneous ET estimates of a crop canopy. The satellite images or remote sensing technique can be used to estimate ET at regional level. However, meteorological data are essential to estimate PET at regional level or farm level if direct measurement methods are expensive or not available.

Table 1. Water use estimates

Parameters	Estimates
Yield kg/ha	1515.01
Total water use mm	720
Plant transpiration mm	544
Soil stage 1 Evaporation mm	88
Soil stage 2 Evaporation mm	131
Initial soil moisture mm	611
Final soil moisture mm	436
Utilised soil moisture mm	175
Total irrigation intake mm	272
Total rainfall mm	396
Effective rainfall mm	251
Rainfall Runoff mm	145
Water Use Efficiency	**2.10**
Transpiration Ratio	**2.78**
Proportion of water inputs	
Rainfall	33%
Irrigation	36%
Soil reserves	23%
Proportion of outputs	
Plant transpiration	71%
Soil evaporation	29%

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Quantifying water use efficiency of irrigated cotton farms in northern NSW.

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Introduction

Water use efficiency is a key issue for the Australian cotton industry. The main focus of this study is to assess the current status of water use efficiency in the cotton industry. This assessment was done using historical water management information already available with the producers. In this project we are looking at both agronomic aspects and the eugineering aspects of water use efficiency of the cotton industry at farm level. A number of water use efficiency indices have been defined for the purpose of assessing the production efficiencies per unit amount of water input at crop level and farm level. The efficiencies of total and irrigation water actually used by the crop during the growing season at farm level were also estimated. The other objectives of this project are to identify the current sources of variation in crop water use efficiency between properties, and to bench mark the current range of water use efficiency in the cotton industry.

A spread sheet model was developed to estimate daily basis moisture content of the soil profile during the growing season. Using this model actual crop water use during the growing season (ET) was estimated using the observed neutron probe moisture data supplemented with simulated figures. This model also estimates net irrigation input, the effective rainfall and the soil moisture reserves depleted during the growing season.

Methodology

A number of progressive farmers representing major cotton growing areas in northern New South Wales were selected to participate in this project with the help of cotton extension officers. The following historical water management information was collected from producers for the last few years depending on availability.

Field level (3-4 fields per season):
Probe readings from selected cotton fields, dates of sowing and dates of harvest, dates of irrigation, lint yield of the selected fields, previous crop.

Farm level:
On farm daily basis rainfall data, total cotton area, total water pumped (for cotton) from river (ML), total water pumped (for cotton) from bores (ML), total on farm harvested water and used storage (ML).

The climatic information required for this analysis was collected from the nearest meteorological station.

Water use efficiency

A number of different efficiencies can be defined for any irrigation system depending on the point of water input and output and the intended use. The efficiency indices for this project were defined according to the objectives of the study. It is also important to define the time scale on which we are working, such as a single irrigation event, growing season or annually. In this project most of the efficiencies have been defined for the growing season. The defined water use efficiencies are as follows.

Production aspects of water use efficiencies

Production efficiencies are water use efficiency indices defined in terms of yield per unit amount of water input

Crop water use efficiency (CWUE): This is the lint yield (kg) produced per mm of water evapotranspired from a cotton field during the growing season. The growing season is the time period from the date of sowing to the date of harvesting.

CWUE (kg/ha/mm) = lint yield (kg per ha) / seasonal ET(mm)..........................1

This can also be expressed in bales per megalitre (ML).

Farm water use efficiency (FWUE): This is the amount of lint (bales) produced per megalitre of water used at the farm level. The total seasonal water usage in an irrigated farm includes pumped water from rivers and bores, the amount used from storage, water harvested during the season, effective rainfall and soil moisture reserves depleted during the season. Soil moisture reserves can be from pre-season rainfall, pre-irrigation or moisture stored during the fallow. The farm water use efficiency can be calculated considering total seasonal water use and yield at the farm level.

FWUE (total water)=total yield (bales)/total seasonal water usage (ML)................2

The yield produced per megalitre of irrigation water is commonly used by farmers to assess their irrigation performances. However, this index is heavily dependent on the amount of rainfall received during the growing season and the amount of soil reserves used. This indicator may he useful for general farm water management activities but is less important in evaluating overall water use efficiency.

FWUE (irrigation water)=total yield (bales)/applied irrigation water (ML).............3

Quantitative water use efficiencies

In an irrigation system, efficiency can be calculated as the ratio of water inputs and water outputs at different points of the system. The two major efficiencies considered in this project are total water use efficiency (TWE) and irrigation efficiency (IE). The total water use efficiency gives an indication of the percentage of water actually used by the crop (ET) from the total water available during the growing season. The irrigation efficiency indicates the percentage of irrigation water evapotranspired from the total irrigation water used at farm level during the growing season.

TWE = seasonal ET (mm)/ total seasonal water usage (mm)...............................4

IE = irri. water used in ET (mm) / total irrigation water used at farm level (mm).........5

The irrigation water evapotranspired during the season is approximately equal to the net irrigation intake, which is the cumulative soil moisture increase due to successive irrigations. Total irrigation water applied includes water pumped from rivers and bores, the amount used from on farm storage and the water harvested during the season excluding rainfall and stored soil moisture.

Estimation of different components of water use

Neutron probe soil moisture information was used in conjunction with a simulation model to estimate seasonal evapotranspiration (ET). The probe data itself is not sufficient to estimate the seasonal ET as probe readings are often not taken regularly enough for this purpose. Therefore, a simulation model was developed to estimate daily basis soil moisture content based on a water balance model. During the simulation, estimated soil moisture figures were adjusted to observed soil moisture figures (probe data) when it was available. In this model the daily ET component was estimated using climatic information. This model estimates seasonal ET, net irrigation intakes (irrigation water used in ET), effective rainfall and the soil moisture reserves used in an irrigated cotton field during the growing season. Data from a number of individual fields per farm per season were analysed and the average figures, across the farm were used in calculating water use efficiencies at the farm level and regional level.

Results

Namoi valley

The average figures from six farms have been used to estimate water use efficiencies in the Namoi valley. It was observed that the average total water use for a farm in the Namoi valley is around 10 megalitres per ha, per season. The average irrigation water input during the last two seasons is around 4-5 megalitres at the farm gate. The average yields for the 96-97 and 97-98 seasons were 7.71 and 8.32 bales per ha and the seasonal total estimated evapotranspiration was 764mm and 781 mm respectively. Water use efficiency indices calculated for the last two seasons are given in table 1. The average crop water use efficiency was approximately 1 bale per megalitre.

Table 1. Water use efficiencies for Namoi Valley

Season	**96/97**			**97/98**		
	Mean	Maximum	Minimum	Mean	Maximum	Minimum
Crop water use efficiency Bales/ML	**1.00**	1.09	0.91	**1.07**	1.23	0.90
FWUE(total water)B/ML	**0.84**	0.92	0.76	**0.83**	0.96	0.68
FWUE(irrigation)B/ML	**1.77**	2.47	1.20	**1.50**	1.88	1.03
Total water efficiency (%)	***0.84***	*0.85*	*0.83*	***0.78***	*0.90*	*0.65*
Irrigation efficiency (%)	***0.68***	*0.80*	*0.54*	***0.63***	*0.79*	*0.42*

Gwydir valley

Data from eight farms were analysed for the Gwydir valley. The average seasonal water use for 96/97 and 97/98 seasons are 17.23 and 17.07 megalitres per ha respectively. However there is a large variation in these total farm water use of between 20 megalitres to 8 megalitres per ha. The average irrigation water use at the farm level is around 11-12 ML with maximum

15 ML to minimum 2.5 ML. The average yield figures for 96-97 and 97-98 are 7.32 and 8.01 bales per ha. The seasonal total evapotranspiration for 96-97 is 715 mm and for 97-98 is 772 mm. Water use efficiency indices calculated for the last two seasons are given in table 2. The average crop water use efficiency was 2.33 and 2.36 kg/ha/mm for 96-97 and 97-98 respectively.

Table 2. Water use efficiencies for Gwydir valley

Season	96/97			97/98		
	Mean	Maximum	Minimum	Mean	Maximum	Minimum
Crop water use efficiency Bales/ML	**1.03**	1.16	0.91	**1.04**	1.20	0.91
FWUE(total water)B/ML	**0.45**	0.76	0.36	**0.48**	0.66	0.38
FWUE(irrigation)B/ML	**0.66**	1.73	0.43	**0.63**	1.03	0.46
Total water efficiency (%)	***0.45***	*0.83*	*0.33*	***0.47***	*0.71*	*0.37*
Irrigation efficiency (%)	***0.38***	*0.62*	*0.28*	***0.44***	*0.66*	*0.33*

Macquarie valley and McIntrye valley

The water use efficiency data for Macquarie valley and McIntyre valley are being analysed and the average efficiency figures calculated so far for these valleys are given in table 3.

Macquarie valley: Data from two farms were analysed. The crop water use efficiency is 2.85 kg/mm/ha and 2.78 kg/mm/ha for 97/96 and 97/98 seasons. The average seasonal total water use for 97/96 and 97/98 seasons are 10 ML and 11.5 ML and the average seasonal ET is 752mm and 819mm.

Table 3. Water use efficiencies for Macquarie valley and McIntrye valley

	Macquarie valley		McIntrye valley	
Season	**96/97**	**97/98**	**97/98**	**98/99**
Crop water use efficiency kg/mm/ha	1.26	1.22	1.02	0.99
FWUE (total) Bales/ML	0.94	0.93	0.80	0.75
FWUE (irrigation) Bales/ML	1.29	1.20	1.33	1.39
Total water efficiency	0.75	0.75	0.79	0.76
Irrigation efficiency	0.66	0.68	0.67	0.60

McIntrye valley: Results from one farm indicates that the crop water use efficiency for 97/98 and 98/99 seasons is 2.30 kg/mm/ha and 2.24 kg/mm/ha. The average total water use during these two seasons are 9.81ML and 9.41ML with 771 mm and 719 mm total seasonal evapotranspiration.

Discussion

The efficiency indices calculated in this project can be used to evaluate the production efficiency of available water and the efficiency of total and irrigation water actually used by the crop (ET) at farm level during the growing season. The most important efficiency indices in this analysis are crop water use efficiency and irrigation efficiency. The crop water use efficiency is the amount of lint yield produced per millimetre of water evapotranspired by the crop. This can be used to evaluate the performance of the farm or paddock with respect to its water use. The irrigation efficiency indicates the losses of irrigation water within the farm. These losses may occur in storage, in the conveyance system or in applications.

Brian Hearn's (1997) provisional benchmark for crop water use efficiency is 3 kg/mm/ha. Most of the crop water use efficiency figures calculated for all the valleys are below this benchmark. There is a huge variability (2.9 kg/ha/mm to 2 kg/ha/mm) in observed crop water use efficiency across the valleys. This indicates that there is considerable room for improvement of crop water use efficiency on some farms. Hearn's benchmark can be achieved by having 10 bales per hectare with 750mm seasonal evapotranspiration.

The irrigation efficiencies observed in this analysis also have a large variability. The irrigation efficiency varies from 80% to 22% across all the valleys for the last few seasons. The low irrigation efficiencies may be due to conveyance losses, storage losses, application losses or improper scheduling. Identifying these points of losses in the farm and taking necessary action to minimise these losses will help to improve the irrigation efficiency.

For example, a farm in the Namoi valley had 42% irrigation efficiency in the 97/98 season. If we can improve this efficiency to the Namoi valley average figure 63%, a large quantity of irrigation water can be saved. This farm used about 7ML/ha of irrigation water and saving 21% of this amount is 1.47ML per hectare. A farm with 200ha of cotton could have saved about 294ML of water and an extra 53ha could have been grown with this saved water. About 477 bales were forgone at the farm average yield of 9bales/ha. So improving irrigation efficiency of this farm to the Namoi valley average figure can make a significant difference to the farm production.

Future work

The study is being extended to other major cotton growing areas and will result in a comprehensive water management database for the cotton industry to assess the current status of water use efficiency at the crop and farm levels. Current major sources of variation in water use efficiency will be identified. Comparisons will be made between various agronomic practices such as tillage and rotation to assess their impact on water use efficiency in a farming systems context.

The outcomes of the project will be used to benchmark the current cotton water use efficiency. A software tool will also be developed for cotton growers to calculate their own water use efficiency figures. The results will also be provided to the extension personnel for extension purposes.

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IRRIGATION SIPHONS AS WATER MEASURING DEVICES

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With increasing demand for limited water resources, it is important to manage irrigation water efficiently. Over the last eighty years the proportion of natural total flow to the sea from the Murray Darling basin which is diverted (mainly for agricultural use) has increased from 15% to 85% (source: ABARE). At the same time, there has been an intensification of public debate around the issue of allocation of water to agricultural, domestic and environmental uses as well as allocation between the industries within the agricultural sector. These changes give added importance to the question of water use efficiency (WUE) over and above the direct importance for the farm manager of making optimum use of a limited production resource.

As part of a project within the Cotton CRC, the CSIRO Cotton Research Unit at Narrabri is investigating the water use efficiency of cotton at the farm and crop level. The results so far indicate that there is a wide variability in irrigation efficiency (the percentage of water actually used by the crop compared to the total irrigation water used on the farm during the growing season) at the farm level: from 80% to 22%.

Water losses can occur at many points in the farm distribution system and there are currently a number of studies underway, in different organisations, that are aimed at identifying the weak points in the system. To identify and prevent these losses, it is important to measure water at various points in the farm distribution system.

If the quantity of irrigation water used at the field level and the amounts pumped from rivers and bores are known, the cumulative storage and conveyance losses can be estimated. This is where the majority of the losses occur. Usually, farmers measure water inputs drawn from rivers and bores, using standard meter gauges for the farm as a whole. However, water inputs to individual fields are not commonly measured due to a lack of simple and effective equipment and techniques.

The quantification of irrigation water used for individual fields and to different enterprises in the farm is also of key importance in maintaining water accounts and better water management. The basic management unit on a farm is the field, and most of the inputs and outputs on a farm are measured at this level. Measurement of irrigation inputs at the field level is required for optimum allocation of limited water to individual fields and different enterprises in your farm. If the soil moisture deficit is known, it would be possible to provide an accurate amount of irrigation water to the crop by measuring water inputs. This would help to avoid losses and to minimise waterlogging conditions. Monitoring and measuring water inputs to individual fields is a key requirement for the calculation of water use efficiencies. As there is considerable variation in physical and chemical properties of soils, land use, location and layout between fields, the water use efficiency among fields could vary significantly. Therefore, the calculation of water use efficiencies at individual field level will help growers to identify fields with low water use efficiencies.

Irrigation siphons provide an immediately available tool to simply measure the amount of water applied to a field. Fundamental flow theories applicable to low pressure pipe systems can be used to calculate the flow rate (discharge in litres per second) from these siphons. When we know the flow rate in the siphons, the quantity of water delivered to a field can be estimated easily and accurately. This article sets out a simple method by which siphons can be used to calculate water application for each irrigation.

DISCHARGE RATE FROM A SIPHON

The discharge rate of a siphon tube is a function of the hydraulic head (figure 1a and 1b), the friction of the pipe and the diameter of the pipe. For a given type of siphon this can be described by a simple and robust equation that requires a single calibration parameter (see box for derivation):

$$Q = Rh^{0.5}$$

Where Q is the rate of discharge, h is the head and R is the calibration constant.

DERIVING THE EQUATION FOR FLOW THROUGH A SIPHON

To calculate the rate that water is discharged from a siphon requires combining a couple of simple physical relationships.

The speed with which the water flows through a siphon due to gravity is determined from the hydraulic head (h). This is the vertical distance from the upper water level to the lower water level as shown in figure 1a and 1b. Using the standard equation for gravitational flow, the velocity is given by:

$$V = \sqrt{2gh}$$

Where, V = velocity, g = the acceleration due to gravity, h = hydraulic head.

The quantity of water (Q) flowing through the pipe per unit time is the product of the velocity (V) of the water and the cross sectional area (A) of the pipe (Q=AV). The cross sectional area of the pipe is calculated using the internal diameter. Combining these two equations, the theoretical discharge equation for a pipe can be written as follows.

$$Q = A\sqrt{2gh}$$

However, the flow of water in a closed pipe is always accompanied by loss of pressure head due to friction. The magnitude of the friction depends on the interior roughness of the pipe walls, the diameter of the pipe, the viscosity of the water and the velocity of the water. The other factors affecting the flow rate are the entrance resistance and exit resistance of the pipe. All these friction factors can be combined into one parameter known as the discharge co-efficient (C), which can be determined empirically. The discharge equation then becomes:

$$Q = CA\sqrt{2gh}$$

The discharge co-efficient (C) calculated for 50mm, 55mm and 60mm siphons are 0.55, 0.60 and 0.63 respectively. For a given pipe $CA\sqrt{2g}$ is a constant and hence the flow rate is dependent only on h. This allows us to derive a single calibration factor R to relate discharge by a given type of siphon to the hydraulic head using the simple equation:

$$Q = Rh^{0.5}$$

In practice, the relationship between discharge rate and hydraulic head fits this function closely. Figure 2 shows the relationship for three different sizes of irrigation siphon in common use: 60mm, 55mm and 50mm external diameters (The internal diameters of the pipes tested were 53.2mm, 48.7mm and 43.8mm). Each curve includes data from three commercial siphons randomly selected from the ACRI and the Auscott Narrabri farms. The pipes were approximately 3.5 metres in length. Slight changes in the length will not have a significant effect on the flow rate. The calibration was done at the hydraulics laboratory of the Charles Sturt University in Wagga Wagga. For practical use, the rate of discharge is also presented in tabular form in Table 1.

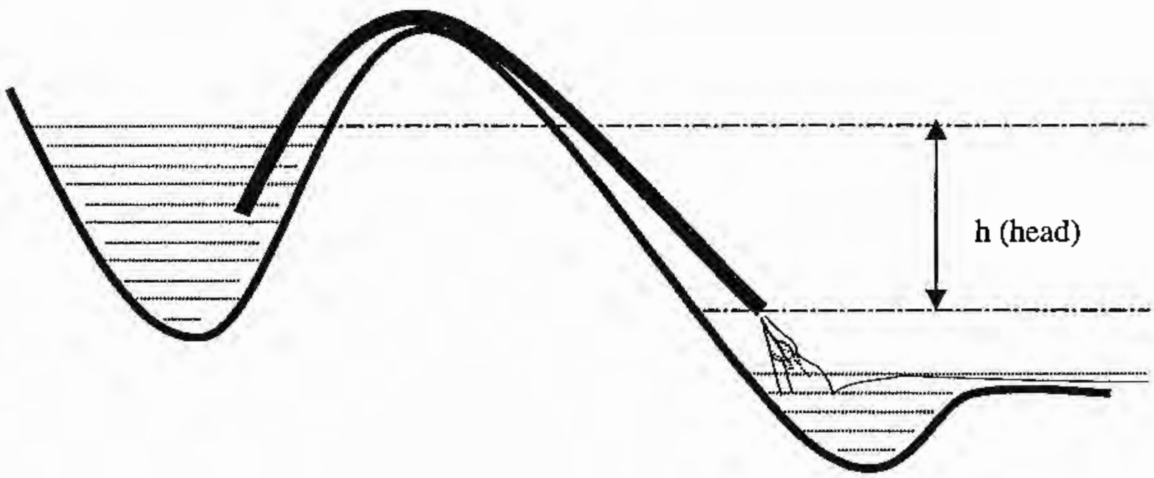

Figure 1a. Free flow

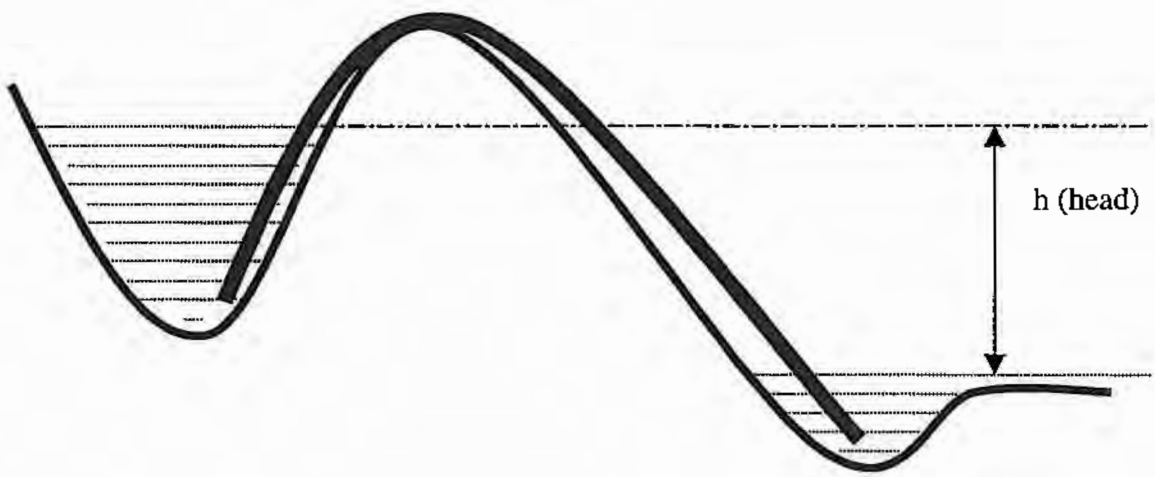

Figure 1b. Submerged flow

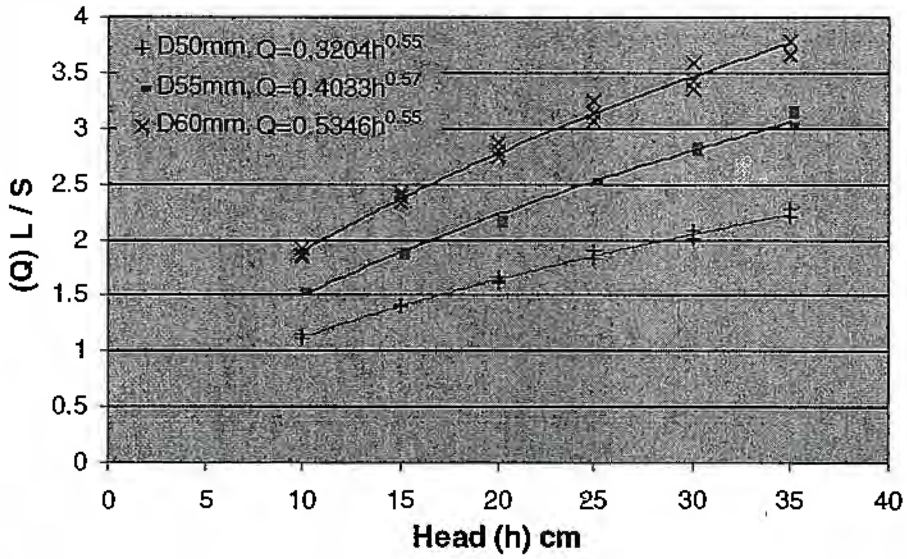

Figure 2. The rate of discharge (litres per second) for three sizes of irrigation siphon as a function of the hydraulic head (cm). Each curve includes data from three randomly selected commercial siphons.

Table 1. Discharge rate (litres per second) for three sizes of irrigation siphon at different hydraulic heads. Siphon length 3.5 metres.

	External Diameter (mm)		
Head (cm)	**50**	**55**	**60**
8	1.01	1.32	1.68
10	1.14	1.50	1.90
12	1.26	1.66	2.10
14	1.37	1.82	2.28
16	1.47	1.96	2.46
18	1.57	2.09	2.62
20	1.66	2.22	2.78
22	1.75	2.35	2.93
24	1.84	2.47	3.07
26	1.92	2.58	3.21
28	2.00	2.69	3.34
30	2.08	2.80	3.47
32	2.16	2.91	3.60
34	2.23	3.01	3.72
36	2.30	3.11	3.84
38	2.37	3.21	3.95
40	2.44	3.30	4.07
42	2.50	3.40	4.18
44	2.57	3.49	4.28

MEASURING THE WATER HEAD

As shown in Figure 1 the outlet of the siphon can be either free flow or submerged. In a free flow situation the water head should be measured by taking the vertical distance from the centre of the outlet siphon to the water level in the head ditch. In submerged situations, the height should be measured from the water level at the outlet to the water level in the head ditch. Establishment of measuring points prior to irrigation makes it easier to measure water heads during irrigation. A long star picket, or something similar, can be driven into the centre of the head ditch and suitably marked to provide a quick and simple way to measure the head. Once the picket is put in place, the maximum possible head needs to be marked on it. A long board is placed across the top of the ditch, extending to the field side and the board checked for level with a spirit level. The vertical distance from the outlet point (free flow) or water level (submerged) in the rotobuck bay to the level of the board (H in the figure 3) is then marked on the picket. If 5cm intervals are then clearly marked from this point on the picket down to the base of the head ditch, it will provide a scale over the maximum possible range of heads. During an irrigation event, the head can then be read directly from the gauge on the picket with the water in the head ditch. The gauge can be improved by attaching a narrow vertical board to the picket to allow a clearer scale to be marked. It can also be made more accurate by adjusting it during the first irrigation event when the actual level of water in the rotobuck bay is known.

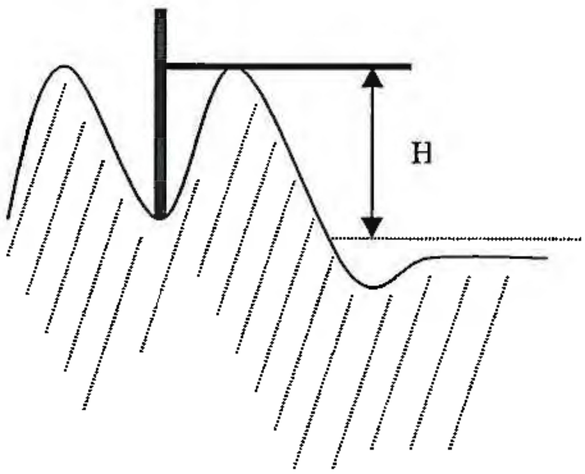

Figure 3. Setting a picket to measure water head in an irrigation channel.

To allow for any slope in the field, establish the measurement point half way along the head ditch. This should give a reasonably accurate estimate. On large fields, there could be a significant difference in the water head between the top and the bottom end. Therefore the accuracy can be improved by taking head measurements at a few points along the head ditch and calculating water delivered as if they are different blocks per each point. When measuring the head during an irrigation, the variation in the water level in the head ditch over time needs to be borne in mind. At the beginning of the irrigation the head will vary depending on the flow rate into the head ditch and how soon the siphons are started. If it is not clear when the water level is stabilised, the level may need to be re-checked a few times over a number of hours until the reading is constant.

CALCULATING THE WATER APPLIED

Having measured the water head in the field, it is possible to estimate the amount of water applied during the irrigation event. The discharge rate per siphon (litres per second) can be estimated from Table 1 using the measured head. Multiplying the discharge rate by the duration of irrigation gives the volume of water delivered to the field through one siphon. Multiplying by the number of siphons used for the field you can easily estimate the total amount of water delivered to the field during the irrigation.

For example, if you have used 200 siphons of 55mm diameter to irrigate a field with 30cm average head for a duration of 10 hours, the total amount of water delivered to the field can be calculated as follows.

Discharge rate from table 1 (litres/second)	=	2.8	L/s
Duration of irrigation (hours)	=	10.0	h
Number of siphons used	=	200	
Duration in seconds			
10×60×60	=	36000	s
Volume per siphon (discharge rate × duration in seconds)			
2.8×36000	=	100800	L
Total volume applied (volume per siphon × number of siphons)			
100800 × 200	=	20160000	L

In this example the quantity of water delivered to the field in the single irrigation event is 20.16 megalitres. The water input per hectare can then be calculated by dividing the quantity applied by the area of the field. The total irrigation water applied to the field during the season can be estimated by summing the amounts applied in the individual irrigation events.

The monitoring and measurement of irrigation water in the farm is very important in managing this limited resource. Field level assessment of water use efficiency will allow growers to identify fields, which need improvements in the pbysical structure of the irrigation system or changes in irrigation strategies. Perhaps some fields may require alterations in farming systems to improve the water use efficiency. Furthermore, quantification of irrigation water at the field level facilitates the maintenance of proper water accounts in the farm. Water accounting will assist in a better understanding of present pattern of water use by individual fields and in the identification of means to achieve water saving and ultimately increase water use efficiency.

Acknowledgments

Funding for the cotton water use efficiency project was provided by the Cotton Research and Development Corporation of Australia. The technical support and facilities provided by the hydraulics laboratory of the Charles Sturt University to calibrate the siphons is also appreciated.

Irrigation Australia 2000 Conference, 23-25 May 2000, Melbourne.

EVALUATION OF CROP WATER USE EFFICIENCY AND FARM LEVEL IRRIGATION EFFICIENCY OF IRRIGATED COTTON FARMS IN NORTHERN NSW AND SOUTHERN QUEENSLAND

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ABSTRACT

In recent years there has been an intensification of public debate around the issue of water allocation to agricultural, domestic and environmental uses as well as allocation between the industries within the agricultural sector. These factors give added importance to the question of water use efficiency over and above the direct importance for the manager of making optimum use of a limited production resource. In this study we are investigating the water use efficiency within the cotton industry at both the crop and farm level. The amount of yield (lint) produced per unit of water used by the crop as evapotranspiration during the growing season (crop water use efficiency) and the percentage of irrigation water supplied to the farm which is actually used by the crop during the season (irrigation efficiency) are being examined.

Water use efficiency was estimated using historical water management data available from cotton producers. Data for the last few seasons were collected from twenty-five farmers representing major cotton growing areas in Australia. This included soil moisture data, dates of sowing, harvesting and irrigation, yield, amount of irrigation water available and rainfall figures. Neutron probe soil moisture information was used in conjunction with a simulation model to estimate seasonal evapotranspiration (ET). This model estimates seasonal ET, net irrigation intake (irrigation water used in ET), effective rainfall and the soil moisture reserves used in an irrigated cotton field during the growing season. Data from a number of individual fields per farm per season were analysed and the average figures across the farm, were used in calculating water use efficiencies at the farm level. The analysis indicates that there was large variation in both total seasonal water usage, which range between 8.2 to 17.2 megalitres (ML) per hectare, and in average seasonal evapotranspiration, which range between 660mm to 850mm. The average crop water use efficiency was 2.5 kg/ha/mm and irrigation efficiency was 60%. Results indicate that there is potential for improved water use efficiencies via improved irrigation design and crop management.

INTRODUCTION

Around 80% of Australian cotton area is irrigated. With the expansion of the cotton industry over the last few decades there has been a significant increase in demand for irrigation water in the cotton growing areas. With this increasing demand the use of irrigation water has become an important issue due to the scarcity of water, competition between domestic, industrial and agricultural users and the requirement for environmental water flows. Further, changes in the ground water level, accumulation of salts and the risk of off-farm contamination by agrochemicals have raised community concerns about the industry. This has imposed increased significance to water use efficiency of cotton farms and on-farm water management. The CSIRO Cotton Research Unit is currently investigating water use efficiency within the cotton industry at both the crop and farm level. A number of water use efficiency indices have been defined for the purpose of assessing the production efficiencies per unit amount of water input at the crop level and farm level. The efficiency with which total and irrigation water was used during the growing season was also estimated at farm level. Using the information collected in this project the current sources of variation in crop water use efficiency between properties and valleys are being identified. Benchmarks for the cotton industry will also be developed.

The current status of cotton water use efficiency was assessed using the water management information available from commercial producers. Most of the cotton growers measure soil moisture using neutron moisture meters for irrigation scheduling and measure water inputs using meters from rivers and bores. Historical water management data for the last two to three years were collected from approximately 25 farmers representing major cotton growing areas in eastern Australia. The information gathered included neutron moisture meter readings, dates of sowing, times of harvesting and irrigation, lint yield, amount of irrigation water pumped and rainfall figures. The climatic information was acquired from the Australian Cotton CRC's meteorological database. The growing season evapotranspiration was estimated using the neutron probe soil moisture data with gaps in the records being filled using the evapotranspiration estimates from an energy balance model. A paddock level analysis was conducted to estimate seasonal evapotranspiration (ET), irrigation water use in ET, rainfall contribution and soil moisture used during the growing season. Data for 300 individual fields were analysed to estimate seasonal evapotranspiration and crop water use efficiency. This project aims to determine mean values for a number of water use efficiency indices and their variation from commercial records.

WATER USE EFFICIENCY

A number of different efficiencies can be defined for any irrigation system depending on the point of water input and output and the intended use. The efficiency indices for this project were defined according to the objectives of the study and specifically for the cotton farms with furrow irrigation. The geographic boundaries used in these definitions are at the farm level. It is also important to define the time scale on which we are working. In this study the efficiencies have been defined over the growing season. The growing season is the time period from the date of sowing to the date of harvesting which is usually between October to April. The defined water use efficiencies are as follows.

Production aspects of water use efficiencies: Production efficiencies are water use efficiency indices defined in terms of yield output per unit amount of water inpnt.

Crop water use efficiency (CWUE): This is the lint yield (kg) produced per millimetre of water evapotranspired from a cotton field during the growing season and is useful in assessing the water use efficiency at crop level.

CWUE (kg/ha/mm) = lint yield (kg per ha) / seasonal ET(mm)...........................1

This is important to evaluate how efficiently the crop produces lint yield with the amount of water consumed in terms of evapotranspiration during the growing period. This can also be expressed in bales (227kg) per megalitre of water consumed.

Farm water use efficiency (FWUE): This is the amount of lint (bales) produced per megalitre of total water used at the farm level. The total seasonal water usage in an irrigated farm includes pumped water from rivers and bores, the amount used from storage, water harvested during the season, effective rainfall and soil moisture reserves depleted during the season. Soil moisture reserves can be from pre-season rainfall, pre-irrigation or moisture stored during the fallow or crop. The farm water use efficiency can be calculated considering total seasonal water available and yield at farm level as follows:

FWUE (total water)=total yield (bales)/total seasonal water usage (ML)................2

The yield produced per megalitre of irrigation water input is commonly used by farmers to assess their water use efficiencies.

FWUE (irrigation water)=total yield (bales)/applied irrigation water (ML).............3

However, this index is heavily dependent on the amount of rainfall received during the growing season and the amount of soil reserves used. This indicator may be useful for general farm water management activities but is less useful in evaluatiug overall water use efficiency or comparing between seasons or locations.

Quantitative water use efficiencies: In an irrigation system, efficiency can be calculated as the ratio of water inputs and water outputs at different points of the system. The two major efficiencies considered in this project are total water use efficiency (TWE) and irrigation efficiency (IE). The total water use efficiency gives an indication of the percentage of water actually used by the crop (ET) compared to the total water available during the growing season.

TWE = seasonal ET (mm)/ total seasonal water available (mm)................................4

The irrigation efficiency indicates the percentage of irrigation water evapotranspired relative to the total irrigation water applied at farm level during the growing season. Irrigation literature contains many irrigation efficiency definitions (Israelsen, 1950; Burt et al., 1997; Barrett and Purcell, 1999). Using the irrigation efficiency definition concepts found in the literature, irrigation efficiency definition for this study was made specifically for the assessment of irrigation water use at the farm level over the growing season. The irrigation water input was measured at the farm level. This efficiency is different from the efficiency of a single irrigation event at field level. For example if irrigation efficiency of a single irrigation event is 60%, it means that 60% of the water delivered is used through crop evapotranspiration. But most of the other 40% flows to surface and sub-surface areas and the surface runoff is usually captured at the tail end and reused. It is mandatory in NSW to recirculate water within the cotton farm due to environmental concerns. When the water is reused, the overall farm efficiency increases. Thus, the irrigation system as a whole farm can be more efficient than a single irrigation event. Seepage, operational spillage and runoff from the tail end, which are often thought of as losses can be reused in the same farm. For such systems, because of multiple reuse the supply of water to the farm can be less than the total (aggregate) amount of water actually applied to crops in successive irrigations. Because of this water multiplier effect the whole farm efficiency can be higher than the efficiency of individual use-cycles.

On farm water harvesting: The traditional way to calculate effective rainfall is the amount infiltrated into the soil in a cropping field from natural precipitation. In this method runoff is considered as a loss to the system. As discussed earlier, farmers are not allowed to discharge the runoff, therefore it would be captured at the tail end and stored for future use. The harvested water will be used as a part of irrigation water and can be counted as an irrigation component in calculating irrigation efficiency. Therefore, in cotton farms the irrigation efficiency can be defined as follows.

$$IE = \frac{CropET - RF_E \ - SM_D}{\text{Total water pumped from rivers and bores + harvested water}}$$

CropET - Total evapotranspiration, **RF_E** - Effective precipitation, **SM_D** - Soil moisture depletion

Practical problems arise in estimating the on farm harvested water as it is not easy to meter every single run-off flow in a farm. The harvested water can be approximately estimated by measuring the water level at the storage before and after a storm. However, water losses generally occurring in storage outside the growing season were not included in this efficiency calculation.

DATA COLLECTION

Existing water management data were collected from commercial cotton producers. A number of farmers representing major cotton growing areas were selected to participate in this project with the help of cotton extension officers. The major cotton growing areas in eastern Australia are shown in Figure 1. The regions covered in this study are the Namoi Valley, Gwydir Valley, Macquarie Valley, McIntyre Valley, Darling Downs and Emerald. These areas represent 90% of total area under cotton. The following historical water management information was collected from producers for the last few years depending on availability.

<u>Field level (3-4 fields per season):</u>

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

<u>Farm level:</u>

- On farm daily rainfall data
- 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)

Other than daily rainfall, the climatic information required for the estimation of evapotranspiration was collected from the nearest meteorological station and the Cotton CRC database.

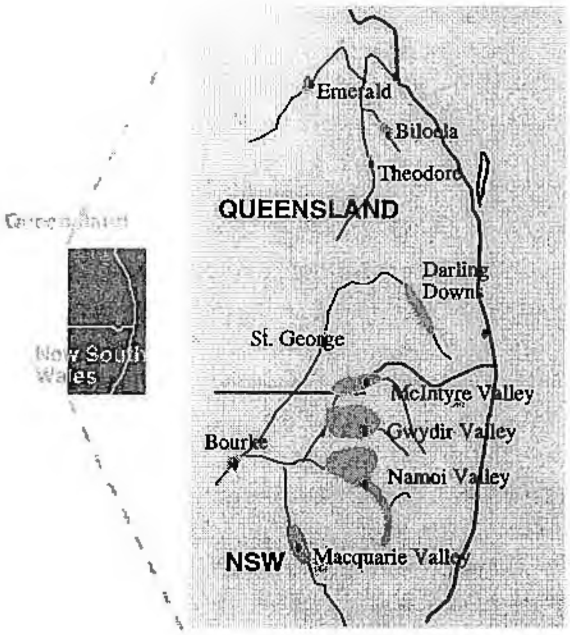

Figure 1. Major cotton growing areas in eastern Australia.

ESTIMATION OF DIFFERENT COMPONENTS OF WATER USE

Estimation of seasonal evapotranspiration is one of the major prerequisites for calculating crop water use efficiency. Seasonal evapotranspiration was estimated by means of moisture changes in the soil profile during the growing season. Soil moisture information was used to calculate the soil moisture profile in a cotton field. However, in most cases, the water content of the soil profile has heen measured at irregular intervals and these readings by themselves were not sufficient to estimate the profile moisture content for the whole season. It is not possible to take accurate moisture measurements at depth less than 20cm using neutron probes, so the measurement at 20cm depth has been used for the moisture content of the top layer of the profile.

From the soil moisture measurements it is also not possible to partition the water use to different components such as transpiration and soil evaporation. Therefore, a daily basis water balance model was developed to simulate the moisture content in the soil profile throughout the growing season. The probe readings were used when readings were available to allow a direct calculation of water use and simulated values were used for missing values. The following water balance model was used to estimate the moisture content of the soil profile. In this model deep drainage losses are considered negligible.

SMC = Pre.SMC + ER + I – ET

SMC = soil moisture content **Pre.SMC** = SMC of the previous day
ER = effective rainfall, **I** = amount of irrigation intake, **ET** = daily evapotranspiration

Estimation of ET: The modified Ritchie (1972) model was used to estimate the daily evapotranspiration. Coefficients as measured for Australian cotton fields by Cull (1979) and Hearn (Personal Communication) were used. This model estimates crop transpiration and soil evaporation separately. The transpiration rate is dependent on the potential evapotranspiration and the leaf area index. The required climatic information to calculate potential evaporation are daily maximum and minimum temperatures, wet bulb temperature and solar radiation. This information was obtained from the Cotton CRC database and from on farm daily rainfall records. The values of daily LAI was calculated using a standard LAI index curve (Constable 1975). In estimating the soil moisture profile, it was assumed that the soil moisture content at sowing (starting date) was equal to the maximum water holding capacity (WHC) of the soil. The WHC of the soil was estimated from the maximum observed soil moisture content. It was also assumed that the soil could absorb water from a rainfall or an irrigation eveut until its maximum water holding capacity was reached with the rest of the water leaving the system as runoff and being harvested for future use. The accurate modelling of rainfall iufiltration into the soil profile was not possible in this study, as only daily basis rainfall figures were available. The amount of water infiltratiug into the soil was calculated by taking the difference between maximum WHC and moisture content prior to rainfall or irrigation. In order to improve the accuracy of the simulation process, whenever the observed values were available the simulated value was replaced by the observed value and the simulation continued from that point until the next observed value was met. An example for simulated soil moisture coutents and the observed soil moisture contents is given in Fig. 2.

This model computes water use in different components and estimates the amount of transpiration and soil evaporation separately. It also calculates the amounts of irrigation, rainfall and soil reserves used by the crop during the growing season. The separate estimation of irrigation water and rainwater used in ET allows us to calculate the irrigation efficiency and the effectiveness of rainfall. The amount of soil reserves used is calculated by subtracting the soil moisture content at harvest/defoliation from the soil moisture content at sowiug. It should be noted that the estimated total water use was not always equal to the total water input from irrigation, effective rainfall and depleted soil moisture hecause of adjustments made when the simulated values were reset to the observed values. This is the fraction of moisture that can not be explained due to the differences between the model estimations and measured values. However, the discrepancy only averaged 7% of total water use.

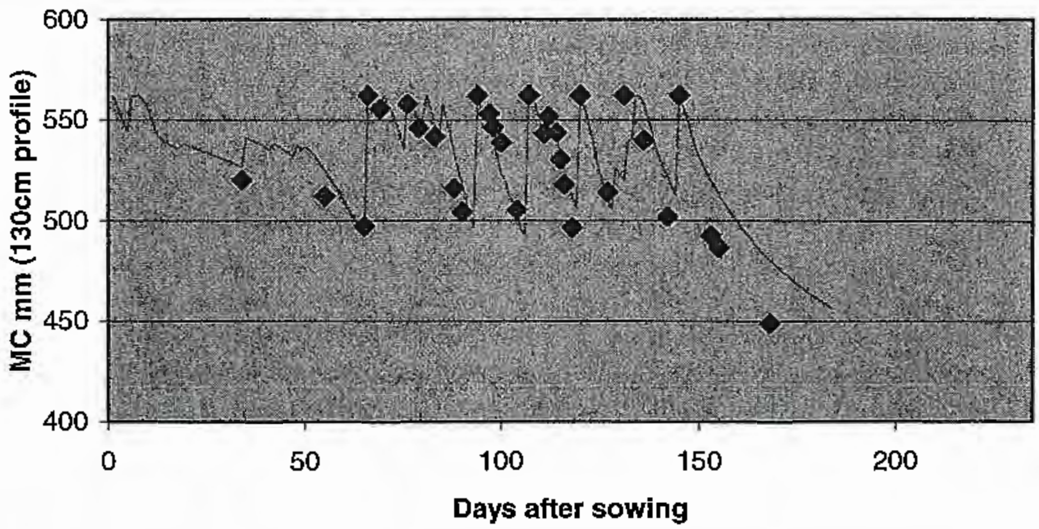

Fig 2. Estimated and observed soil moisture contents (not adjusted). Dots are observed values and the line is estimated moisture content in millimetres for a 130cm profile.

RESULTS

The major sources of water supply to Australian cotton farms were rainfall and irrigation with some contributions from the stored soil moisture. The long-term average growing season rainfall (October to March) varies from 270mm to 500mm. The amount of irrigation water pumped from rivers and bores and the amount of on-farm harvested water varied widely between the valleys (Table 1).

Most of the cotton growing soils can store up to 1.5ML of available water per hectare and this amount is dependent on pre-season rainfall, land use pattern and water holding capacity of the soils. The contribution from natural rainfall within the season to meet crop water requirement (effective rainfall) and the used soil moisture reserves are given in Table 2.

Table 1. The amount of water pumped from rivers and bores and on-farm harvested water for different valleys

	96/97		97/98		98/99	
Region	Pumped ML	Harvested ML	Pumped ML	Harvested ML	Pumped ML	Harvested ML
Namoi Valley	4.71	0.87	5.16	0.72		
Gwydir Valley	11.86	2.00	12.23	1.33		
Macquarie Valley	7.86	0.19	8.36	1.18		
McIntyre Valley			5.70	0.19	2.18	2.90
Darling Downs			3.13	3.00	2.22	2.20
Emerald			6.30	1.19	3.23	0.67
Mean	**8.14**	**1.02**	**6.81**	**1.27**	**2.54**	**1.93**

Table 2. Contribution from rainfall and soil reserves for seasonal evapotranspiration in different valleys
(SM – soil moisture reserve, RF - Rainfall)

	96/97		97/98		98/99	
Region	Effective RF mm	Used SM mm	Effective RF mm	Used SM mm	Effective RF mm	Used SM mm
Namoi Valley	321	132	308	126		
Gwydir Valley	213	124	220	132		
Macquarie Valley	231	114	118	20		
McIntyre Valley			344	48	343	97
Darling Downs			265	182	299	110
Emerald			191	122	378	96
Mean	**255**	**123**	**241**	**105**	**340**	**101**

Seasonal evapotranspiration: The amount of total evapotranspiration is mainly dependent on the evaporative demand. For irrigated cotton the total growing season water use for individual fields varied from 600mm to 1000mm. The average estimated seasonal ET in millimetres for different valleys are given in the Table 3.

Table 3. Seasonal evapotranspiration in millimetres for different valleys as calculated from soil moisture data and simulated figures

	96/97			**97/98**			**98/99**		
Region	**Mean**	Max	Min	**Mean**	Max	Min	**Mean**	Max	Min
Namoi Valley	**764**	968	690	**781**	886	731			
Gwydir Valley	**715**	763	670	**772**	819	732			
Macquarie Valley	**800**	925	752	**853**	888	828			
McIntyre Valley				**771**	779	764	**719**	735	694
Darling Downs				**673**	719	626	**664**	708	623
Emerald				**682**	731	652	**700**	737	677
Mean	**760**			**755**			**694**		

Crop water use efficiency

In general, plants are not exposed to any water stress in the cotton industry. Yield reductions are not intended with restricted irrigation. Therefore, in most of the irrigated cotton farms, evapotranspiration will not be affected by stress. The calculated average CWUE varied from 2.2 kg/ha/mm to 2.9 kg/ha/mm (0.9-1.4 bales/ML) and is given in Table 4.

Table 4 Crop water use efficiency kg/ha/mm as calculated from actual yield figures and seasonal evapotranspiration.

	96/97			**97/98**			**98/99**		
Region	**Mean**	Max	Min	**Mean**	Max	Min	**Mean**	Max	Min
Namoi Valley	**2.30**	2.47	2.06	**2.43**	2.79	2.03			
Gwydir Valley	**2.33**	2.62	2.06	**2.36**	2.73	2.06			
Macquarie Valley	**2.85**			**2.78**	2.95	2.59			
McIntyre Valley				**2.30**			**2.24**		
Darling Downs				**2.70**	2.86	2.55	**2.88**	3.17	2.55
Emerald				**2.53**	2.80	2.12	**2.45**	2.56	2.34
Mean	**2.49**			**2.52**			**2.52**		

The farm water efficiency, which is the number of bales produced per unit water input to the farm, is also an evaluation parameter of water use efficiency. The production per unit water input has been calculated for the total water input and for irrigation water input separately and are given in Table 5. The farm water use efficiency for total water varied from 0.38 bales/ML to 1.27 bales/ML. The calculated farm water use efficiency for irrigation water varies from 0.43 bales/ML to 3.28 bales/ML. Usually most of the producers measure water use efficiency by the amount of yield (lint) produced per unit amount of irrigation water input. This parameter is heavily dependent on the amount of rainfall received during the growing season and the amount of soil reserves used. Since the seasonal rainfall varies largely spatially and from season to season, the use of this parameter in evaluating water use efficiency is not appropriate.

Table 5. Mean number of bales produced per ML of total water and irrigation water used at farm level

	Total water (Bales/ML)			**Irrigation water (Bales/ML)**		
Region	**96/97**	**97/98**	**98/99**	**96/97**	**97/98**	**98/99**
Namoi Valley	0.79	0.83		1.60	1.50	
Gwydir Valley	0.45	0.48		0.66	0.63	
Macquarie Valley	0.94	0.93		1.29	1.20	
McIntyre Valley		0.80	0.75		1.33	1.39
Darling Downs		0.79	1.01		1.42	2.14
Emerald		0.72	0.88		1.03	2.04
Mean	**0.73**	**0.76**	**0.88**	**1.18**	**1.19**	**1.86**

Irrigation efficiency

Irrigation efficiency, the water actually used by the crop compared to the water input is an important parameter to evaluate the system in terms of water savings. This parameter can be used to evaluate water losses within the farm. The observed irrigation efficiency for individual farms varied from 20% to 85%. The irrigation efficiency calculated in this project is the combination of storage, conveyance and application efficiencies for the whole growing season. Estimation of storage, conveyance and application efficiencies are being conducted in four selected cotton farms in the McIntyre valley by the University of Southern Queensland as a separate project. The calculated irrigation efficiencies for northern NSW and southern Queensland cotton farms are given in Table 6. The observed average total water use efficiency (fraction of seasonal ET compared to the total available water) was around 70% (data not presented).

DISCUSSION

The amount of total water used for irrigated cotton varied significantly from farm to farm and season to season depending on the geographic location of the farm and climatic variations. The range of observed total water use during the growing season in all valleys was between 17.2 ML/ha and 8.5 ML/ha. The average amount of irrigation water pumped from rivers and bores for different valleys vary from 2.2 ML/ha to 12.2 ML/ha and the on-farm harvested amounts vary from 0 to 3.2 ML/ha. These differences in total water and irrigation water use may be due to the differences in soil types, climatic conditions, locations, farm layout, water sources and management. These are currently being investigated.

Table 6. Average irrigation efficiencies for different valleys

	96/97			**97/98**			**98/99**		
Region	**Mean**	Max	Min	**Mean**	Max	Min	**Mean**	Max	Min
Namoi Valley	**0.60**	0.80	0.20	**0.63**	0.79	0.42			
Gwydir Valley	**0.37**	0.62	0.22	**0.42**	0.66	0.32			
Macquarie Valley	**0.66**			**0.68**	0.86	0.50			
McIntyre Valley				**0.67**			**0.60**		
Darling Downs				**0.40**	0.51	0.29	**0.62**	0.76	0.44
Emerald				**0.50**	0.54	0.42	**0.59**	0.70	0.36
Mean	**0.54**			**0.55**			**0.60**		

The actual seasonal crop water use (ET) also varied considerably from location to location and season to season with the overall average around 740mm. The highest seasonal mean crop water use of 853mm was observed for the Macquarie valley and the lowest seasonal mean crop water use of 664mm was observed for the Darling Downs. The higher values in the Macquarie Valley may be due to deep percolation losses, which were not considered in the water balance model in estimating seasonal ET. Even though the deep drainage losses are negligible in the Namoi valley (Douglas 1997) and other vertisol soils, the deep drainage losses are relatively high in the Macquarie valley (Willis et al 1997) which is the only area in this study not dominated by vertisols. With regards to seasonal variations the 97/98 season had higher ET values than 96/97 and 98/99 seasons. This is most likely due to the higher temperatures, which prevailed during the 97/98 season compared with the other two seasons.

The average crop water use efficiency observed for all of the valleys and seasons was 2.5 kg/ha/mm with large variability across the valleys. The maximum crop water use efficiency of 3.2 kg/ha/mm was observed in Darling Downs and the lowest of 2.0 kg/ha/mm was observed in the Namoi valley. According to the results obtained in this study, Hearn's (1997) benchmark for crop water use efficiency of 3kg/ha/mm is an acceptable target for commercial properties. However a majority of the crop water use efficiency figures calculated for all the valleys in this study are below this benchmark. This indicates that there is considerable room for improvement of crop water nse efficiency on some farms. Improving crop water use efficiency from 2.5 kg/ha/mm to 3kg/ha/mm with 750mm seasonal ET will resnlt in producing an additional 1.65 bales per hectare with the same water use. Hearn's benchmark (3 kg/ha/mm) can be achieved by yielding 10 bales per hectare with 750mm seasonal evapotranspiration. Farm water use efficiency, across the valleys in terms of bales per total seasonal water available varied from 0.5 to 1 bales/ML and the average output per irrigation water input in all valleys and seasons varied from 0.6 to 2.1 bales per ML. Improved crop water use efficiency can be achieved not only through improved irrigation management but will also be strongly influenced by other management factors affecting yield such as nutrients, insects, weeds and soil management together with better crop rotations.

The irrigation efficiencies observed in this analysis also have large variability. The average irrigation efficiency for all the valleys varied from 37% to 68% for the last few seasons and the observed irrigation efficiencies for individual properties varies from 20% to 85%. The average irrigation efficiencies for 96/97, 97/98 and 98/99 were 54%, 55% and 60% respectively. According to the international standard the attainable efficiency with furrow irrigation is in between 60 % to 75% (Solomon 1993), so the current irrigation efficiency of Australian cotton farms are reasonable compared to the reported standards. However, the results indicate that the irrigated cotton crop actually uses only just above half of the irrigation water applied at the farm level and around 40 to 45 percent is lost within the farm. Some components of these losses may be contributing to re-charge of the ground water and may be being re-used through bore pumping for future irrigations in the same property or in other locations. If there are runoff losses, it could be an input to a property downstream of the command area. These factors have to be considered in the assessment of irrigation efficiency at regional level.

Some of the low irrigation efficiencies observed in this study may be due to conveyance losses, storage losses, application losses or improper scheduling. Identifying these points of losses in the farm and taking necessary action to minimise these losses will help to improve the irrigation efficiency. For example, a farm in the Namoi Valley had 42% irrigation efficiency in the 97/98 season. If we can improve this efficiency to the Namoi Valley average figure of 63%, a large quantity of irrigation water can be saved. This farm used about 7ML/ha of irrigation water and saving 21% of this amount is 1.47ML per hectare. A farm with 200ha of cotton could have saved around 294ML of water and an extra 53ha could have been grown with this saved water. About 477 bales were forgone at the farm average yield of 9bales/ha. So improving the irrigation efficiency of this farm to the Namoi Valley average figure can make a significant difference to the farm production.

The efficiency indices calculated in this project can be used to evaluate the production efficiency of available water and the efficiency of total and irrigation water actually used by the crop (ET) at farm level during the growing season. The most important efficiency indices in this analysis are crop water use efficiency and irrigation efficiency. The crop water use efficiency can be improved by better management of the crop to achieve the maximum return from depleted water use. The irrigation efficiency indicates the losses of irrigation water within the farm and improving this efficiency could make a huge impact to the cotton industry by saving water, preventing environmental damage and finally increasing production. The analysis is being continued to identify sources of variation in water use efficiencies and to develop regional level benchmarks.

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MANAGING WATER USE EFFICIENCY ON FARMS

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Maximising water use efficiency (WUE) means maximum returns from a scarce resource. In addition, increasing public debate about water use adds a political imperative to get it right. A survey of current performance shows that while some growers are performing well, others have aspects that require attention.

The first step toward managing WUE is to measure current performance. Proper measurement will provide a comparison against the performance of other producers in your area and against industry standards. It will also help identify where losses are occurring.

Introduction

Water use has become an important issue locally and globally. There is increasing competition between agricultural, industrial, domestic and environmental sectors. Concurrent with this increase in competition, there has been increasing public debate about water and environmental issues. This imposes additional pressure on irrigators, including cotton growers, to be accountable for the way water is used.

Even without these external pressures, water use efficiency (WUE) is a key issue for producers. If water is a limiting resource, optimising production per unit of available water is clearly an important component of maximising returns. Further, inefficiencies in water use may indicate losses from the system which can cause additional difficulties on the property: excessive run-off leading to erosion, seepage leading to localised ground water rise and possibly salinisation.

To assess the current water use efficiency within the cotton industry we calculated water use efficiency at the crop and the farm level using producers' historical water management data. A whole farm water use efficiency was calculated and then two components of this: the efficiency with which water was supplied to the crop (irrigation efficiency) and the efficiency with which the crop converted the water it actually used into lint (crop water use efficiency).

Our results indicate significant opportunities for improving water use. Using this simple technique, producers can assess their own water use efficiency and compare their performance to others in their area or to industry benchmarks.

Indices of Water Use Efficiency

The overall efficiency of production of a cotton farm can be characterised using a whole farm water use efficiency (FWUE); calculated as the lint production (bales) per unit of water supplied for crop production.

FWUE (total water)=total yield (bales)/total seasonal water supply (ML).

This index takes into account all available sources of water including rainfall, irrigation water from rivers or bores and possibly overland flow. When assessed over a growing season the depletion of stored soil moisture may also be considered an input. FWUE can be simply transformed into an economic efficiency by multiplying yield by market price.

For irrigated production, FWUE can also be calculated on the basis of irrigation water inputs alone:

FWUE (irrigation water)=total yield (bales)/applied irrigation water (ML).

While this approach has a certain appeal for gauging the efficiency with which irrigation water is used, the efficiency figure obtained is beavily dependent on the initial soil moisture storage, and the amount of rainfall the crop receives. It is therefore less useful for comparing efficiency between seasons or locations or for evaluating water savings than FWUE based on total water.

The water inputs for crop production are dissipated througb a uumber of mechanisms. Non-beneficial losses include surface run off, deep drainage, and application and storage losses. Evapotranspiration can be considered to be the water that is productively used by the crop. This is the water transpired during the course of the season, together with a certain amouut of water which is inevitably evaporated from the soil surface and free water surfaces within a cropped field. Evapotranspiration can be used to divide FWUE into its two primary components: irrigation efficiency and crop water use efficiency as described below.

Irrigation efficiency (IE) can be calculated at the whole farm level by calculating the perceutage of irrigation water actually used by the crop (as evapotranspiration) relative to the total irrigation water inputs at the farm level available during the growing season.

$$IE = \frac{ET - RI - SM_D}{\text{Total water supplied froiu rivers, bores and storages}}$$

ET = Evapotranspiration over the growing season, RI = Rainfall that infiltrates in the crop, SM_D = Soil moisture depleted over the growing season.

This is different from the efficiency of a single irrigation event at the field level. IE based on single events cannot be used to make assessments and recommendations at the whole farm level. The harvesting and reuse of tail water means that the water is not lost from the farm system, although it is generally assessed as a loss when considering a single irrigation event. Thus, it is possible for the irrigation system of the whole farm to be more efficient than a single irrigation.

The ratio of water inputs and water outputs at different points of the irrigation system can be calculated to reflect the efficiency of different components of the farm system. Storage, conveyance, application and distribution efficiencies are commonly used indices. The index for whole farm irrigation efficiency used in this paper groups all these components.

Crop water use efficiency (CWUE) is the lint yield (kg/ha) produced per millimetre of evapotranspiration used over the growing season. This index quantifies how efficiently the crop produces lint yield from the amount of water actually consumed by the crop.

CWUE (kg/ha/mm) = lint yield (kg per ha) / seasonal evapotranspiration (mm).

It should be noted that since CWUE and FWUE are ratios that include the yield of the crop, they can be effected by any factor which alters yield, not only those relating to water management.

Assessing Current WUE in the Cotton Industry

To assess the current water use efficiency within the cotton industry we calculated the above indices using producers' historical water management data. Data were collected from approximately 25 farmers across the major cotton growing areas. The following information was collected for the last few years depending on availability.

Field level (3-4 fields per farm per season): Neutron probe readings, date of sowing and harvesting, dates of irrigation, lint yield, previous crop, and soil type

Farm level: On farm daily rainfall data, total cotton area, total water pumped (for cotton) from the rivers (ML), total water pumped (for cotton) from bores (ML), total water harvested on farm and stored water used (ML)

Other than daily rainfall, the climatic information required for the analysis was obtained from the nearest meteorological station.

Firstly, FWUE was calculated. We then calculated actual crop water use (evapotranspiration) and thence CWUE and IE. All efficiencies were calculated across the whole growing season: from sowing to harvest. Water losses occurring in storage outside the growing season were not included in the calculation.

Since evapotranspiration was needed for calculating both CWUE and IE, a good estimate was needed to allow us to partition FWUE into its components. Evapotranspiration was calculated from a combination of observed soil moisture changes (from neutron probes) and a daily soil moisture balance. Probe data were used when possible to allow a direct calculation of water use. When probe data were unavailable or were interspersed with unmeasured rainfall, evapotranspiration was calculated from meteorological data using the modified Ritchie (1972) model. In this model, deep drainage losses are considered negligible.

Measured Water Use Efficiency

Farm water use efficiency

The average yields across the participating farms are given in Table 1 along with the evapotranspiration and the water use efficiencies derived. Farm water use efficiency varied from 0.38 bales/ML to 1.27 bales/ML when based on total water input and from 0.43 bales/ML to 3.28 bales/ML when based on irrigation water inputs. Examining the components of FWUE (CWUE and IE) allows us to explore the sources of this variation.

Table 1. The average yield from participating farms (bales/ha), evapotranspiration and the water use efficiency indices calculated. Numbers in parentheses indicate the observed range.

	1996-1997	1997-98	1998-99
Yield (bales/ha)	8.14	8.38	7.66
Evapotranspiration	760 *(670-698)*	755 *(626-888)*	694 *(623-737)*
Farm WUE (bales/ML):			
Total water	**0.73**	**0.76**	**0.88**
Irrigation water	1.18	1.19	1.86
Crop WUE (kg/mm)	**2.49** *(2.06-2.62)*	**2.52** *(2.03-2.95)*	**2.52** *(2.34-3.17)*
Irrigation efficiency (%)	**54** *(0.20-0.80)*	**55** *(0.29-0.86)*	**66** *(0.36-0.76)*

Crop water use efficiency

The average CWUE observed was 2.5 kg/ha/mm. There was a high degree of variability between producers but the average was very similar for the three seasons of the study. The maximum CWUE observed for a farm was 3.2 kg/ha/mm and the lowest was 2.0 kg/ha/mm (Table 1).

To examine the effect of crop water use on lint yield, the yield from individual fields were plotted against seasonal evapotranspiration by the crop. There was a positive relationship between evapotranspiration and yield up to about 700 mm. However, beyond this, additional water consumption did not increase yield (Fig. 1). This relationship has been demonstrated previously in experimental data. The broken line in the figure is the relationship derived by Orgaz and co-workers (1992) who studied water use by cotton when managed with different irrigation deficits. Our results demonstrate that the relationship applies in the commercial situation also. The yield plateau results from a decline in the proportion of lint produced relative to the whole plant weight (Orgaz et al. 1992). The total dry weight produced continues to rise above an evapotranspiration of 700 mm but, while there is more vegetative growth, there is no increase in reproductive output.

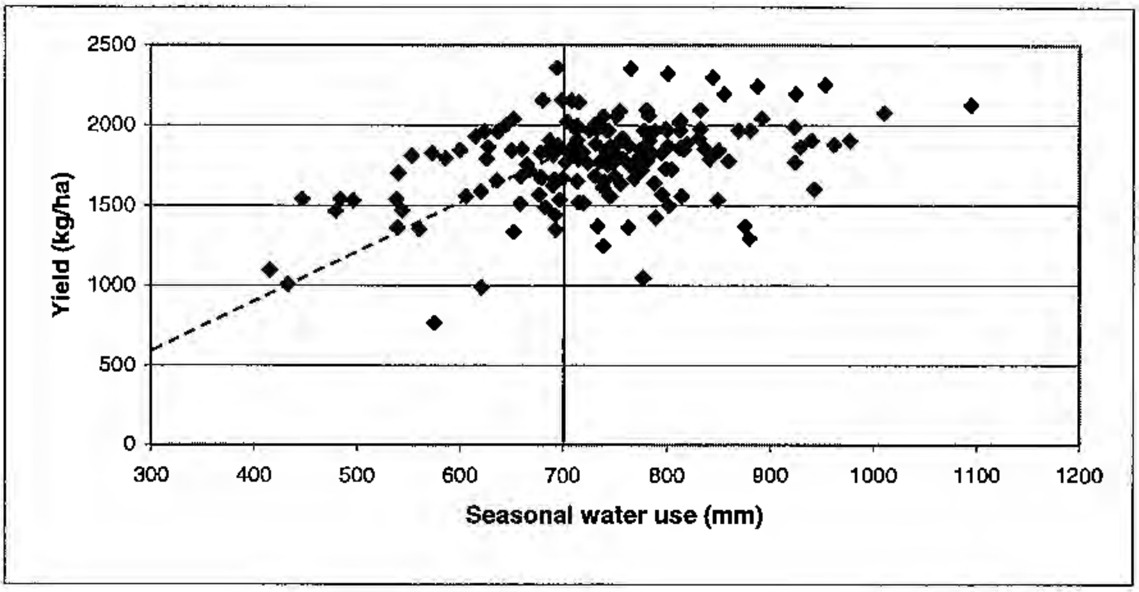

Figure 1. Relationship between lint yield (kg/ha) and seasonal evapotranspiration (mm) obtained from producer's data. The broken line shows the relationship found by Orgaz and co-workers (1992) from experimental studies.

As a result of the relationship between evapotranspiration and yield, CWUE was relatively constant up to 700 mm and then declined (Fig 2). The average CWUE for crops using up to 700 mm was 2.7 kg/ha/mm, indicated by the broken line. Combining the responses for CWUE and yield, the target evapotranspiration for a crop should be taken to be around 700 to 800 mm. Below this level, yield is being sacrificed. Above this, water is being wasted with no advantage in yield being achieved. Further, the risk of waterlogging is increased (Hearn and Constable 1984).

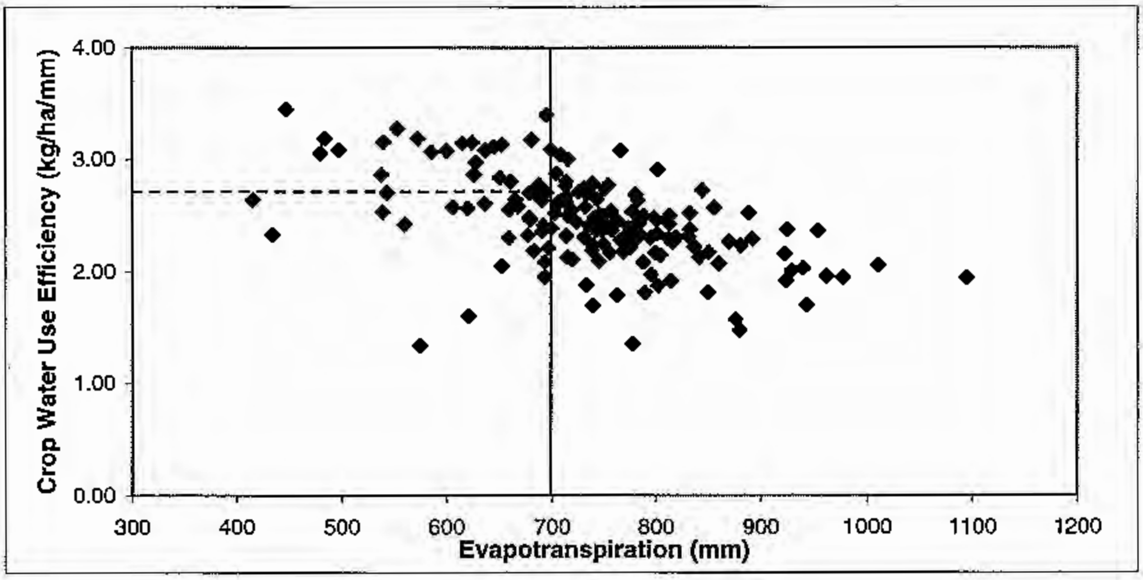

Figure 2. Relationship between crop water use efficiency and evapotranspiration for individual fields in this study. The broken line indicates the average CWUE (2.7 kg/ha/mm) for fields where evapotranspiration was less than 700 mm.

There are a number of management options which can be manipulated to help achieve evapotranspiration in the target range. In situations of excessive evapotranspiration, the most apparent factor to consider is irrigation strategy. Excessively frequent irrigation is known to promote vegetative growth at the expense of fruit. This in turn increases the crop water demand further. Mild water stress prevents excessive vegetative growth and promotes yield development. Optimal irrigation strategies have been explored in the past by a number of authors including Constable and Hearn (1981) and Hearn and Constable (1984).

High nitrogen predisposes a crop to excessive leaf development. Clearly, a proportionately high water supply is also needed, but if this should become available through rainfall or over irrigation, excessive nitrogen will promote luxuriant growth. Nitrogen application rates based on soil testing will prevent over application. Whether high levels of nitrogen or water are anticipated or not, monitoring crop vigour will allow timely application of Pix if excessive vegetative growth begins.

If evapotranspiration is too low, again the first management factor to examine is irrigation strategy. Irrigation interval and the timing of the first irrigation are obviously basic to developing a plant of adequate size. The impact of inadequate water supply is to reduce evapotranspiration and yield proportionately. The result is a low yielding crop but with CWUE not effected. Inadequate nitrogen has the same impact. Leaf area is very sensitive to low nitrogen. Low leaf area in turn reduces evapotranspiration and yield.

Variation in CWUE can occur not only through water supply but it is also influenced by any management factors affecting yield such as nutrient, insect, weed and soil management. This causes the vertical scatter of points in Figures 1 and 2, seen at all evapotranspiration levels.

Some of these factors may act through reducing plant size and hence cause a commensurate reduction in yield and evapotranspiration. However, if the development of the fruit is effected disproportionately compared to vegetative growth, the result can be a reduction in yield with little reduction in water use; and hence a reduced CWUE. Insect damage can suppress yield directly through the loss of fruit and hence depress CWUE. It is also possible that if there is sufficient time and resources available to the crop it may promote excessive growth due to the removal of the fruit demand on resources.

Hearn (1997) proposed a target for CWUE of 3 kg/ha/mm. This is a high but achievable objective for commercial properties; being exceeded in a number of the commercial crops in our study (Fig 1). However, the wide variability in CWUE as seen in Fig 1 and the predominance of CWUE values below 3 kg/ha/mm, indicate that there is considerable room for improvement on some farms. A CWUE of 3 kg/ha/mm can be achieved by yielding 9.3 bales per hectare with 700 mm seasonal evapotranspiration. Improving CWUE from 2.5 to 3 kg/ha/mm with 700 mm seasonal evapotranspiration will result in producing an additional 1.25 bales per hectare with the same water use or a saving of about 17% of water which could be used for the production of additional irrigated crops.

Irrigation efficiency

Whole farm irrigation efficiency in our study averaged 57% (Table 1) but there was a large variability. The observed irrigation efficiencies for individual properties varied from around 25% to 80%. The results indicate that the irrigated cotton crop actually uses just over half of the irrigation water supplied at the farm level. Around 40 to 45% is lost within the farm system through conveyance, storage and application losses or improper scheduling. Clearly, with some properties having figures as low as 25%, identifying where these losses are occurring and rectifying the problems presents significant opportunity to improve the efficiency with which irrigation water is used. Paul Dalton and Steve Raine of The University of Southern Queensland are currently conducting research to develop methods that can be used by producers to identify where irrigation water is being lost during storage, distribution and application and to improve application techniques. Evaporative losses have been shown to be a large factor in IE.

As for the CWUE, Hearn's (1997) proposed target for IE of 75%, is a high value but achievable. It was achieved in 10% of the year x season combinations in this study. Because of the constraints of location, farm design and soil type not all producers will be able to approach this objective without significant capital investment. However, if very low IE is indicated, there are clearly grounds for further investigation using some of the techniques being developed by The University of Southern Queensland.

Recommendations

The most important step toward managing water use efficiency on farm is to start measuring your water use. The wide variation in both CWUE and IE indicates that there is significant potential for many producers to increase their efficiency. The data requirements for the type of analysis conducted here are relatively simple and are already collected by many producers, although the full set is rarely recorded on any one farm. In collaboration with the CottonLOGIC team, a software tool is being developed to assist producers to record the appropriate data and analyse their water use efficiencies at the field and farm level. It will allow proper comparisons to be made against benchmarks or other local producers. It will also assist in identifying ways of increasing efficiency specific to a producer's property.

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Assessment of Water Use Efficiency of Irrigated Cotton Using Producer's Data

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Abstract

Water use efficiency is a key issue for the Australian cotton industry. The current status of on-farm water use and water use efficiency were assessed using the historical water management information available from producers. A number of water use efficiency indices at crop and the farm level were calculated across the industry. The seasonal crop water use was estimated using the neutron probe soil moisture data with gaps in the records being filled with soil moisture figures derived from a daily soil water balance. Around 200 individual sets of field data were analysed to estimate seasonal evapotranspiration and actual irrigation water consumption. The average crop water use efficiency was 2.5 kg/mm/ha and the average farm level irrigation efficiency was 57% but both were highly variable. Despite the high efficiency in terms of return per unit of water use there is room for further improvement in crop water use efficiency and irrigation efficiency in many cotton farms.

Key words: cotton, water use efficiency, irrigation

INTRODUCTION

The Australian cotton industry consumes a considerable quantity of surface and ground water for irrigation. There are 400,000 hectares of irrigated cotton in eastern Australia and more than 95% of this is furrow irrigated. During the last few decades the expansion of the industry has lead to an increase in the demand for irrigation water. With this increasing demand, on-farm water use has become an important issue due to the scarcity of water, competition between domestic, industrial and agricultural users and environmental issues. This has imposed increased significance on water use efficieucy in cotton farms. We conducted a survey to assess the current status of water use efficiency of the cotton industry at both the crop and farm levels. Using the data collected from commercial producers, both production and quantitative water use efficiencies were calculated across the industry.

METHODOLOGY

A number of water use efficiency indices were defined to assess the production and quantitative water use efficiencies. Crop water use efficiency (CWUE) is the lint yield (kg) produced per millimetre of water evapotranspired from a cotton field during the growing season. Farm water use efficiency is defined as the number of bales produced per total water input and irrigation water inputs at farm level. The farm level irrigation efficiency was calculated by the percentage of irrigation inputs at the farm gate used in evapotranspiration during the growing season. The time scale used in these definitions was the growing season (October to March) and the water losses outside the growing season were not included. Historical water management data for the last two to three years were collected from approximately 25 farmers representing major cotton growing areas in eastern Australia. This data include neutron probe soil moisture readings, date of sowing, harvesting and irrigation, lint yield, total cotton area, irrigation inputs and climatic data. The actual crop water use (ET) was estimated by means of moisture changes in the soil profile during the growing season. Daily basis volumetric moisture content in the soil profile was estimated for the whole season using measured data and simulated figures. A desktop methodology was developed to estimate irrigation, rainfall and soil moisture reserve contributions to seasonal evapotranspiration of a cotton field (Tennakoon and Milroy 2000). A number of fields per season per farm were analysed and the average values for farms and valleys were calculated.

RESULTS AND DISCUSSION

The major sources of water inputs to cotton farms are in-season rainfall, irrigation and soil moisture stored during the winter period. The estimated average water inputs from different sources in megalitres per hectare are given iu Table 1. The average total water use at the farm level was 11 megalitres per hectare per season including approximately one megalitre from depleted soil moisture. However, water consumption in a cotton farm varied widely depending on the soil type, location and season. The lower irrigation input values for 98/99 season is mainly due to higher proportionate of data collected from Queensland cotton farms.

Table 1. Average water inputs to cotton farms in megalitres/ha calculated from the survey group.

Season	**96/97**	**97/98**	**98/99**
Pumped from rivers and bores	8.1	6.8	2.5
Effective rainfall	2.6	2.4	3.4
On-farm harvested	1.0	1.1	1.9
Used soil reserves	1.2	1.1	1.0
Total water usage	**12.9**	**11.4**	**8.9**

The average seasonal ET and water use efficiencies for the last few seasons are given in Table 2. The mean seasonal ET was 740mm. There was a positive linear relationship between yield and seasonal ET up to 700mm. However, use of seasonal ET above 700mm reduced the CWUE because yield did not continue to increase. The average CWUE was approximately 2.5 kg/ha/mm for across the seasons. Hearn (1999) proposed an industry benchmark of 3 kg/ha/mm. Our results indicate that this is achievable on commercial properties. Improving CWUE from current average 2.5 to 3 kg/ha/mm will produce an additional 1.6 bales (1bale = 227kg) per hectare with 740 mm seasonal ET. Production per megalitre of total water input averaged around 0.8 bales and the overall average per megalitre of irrigation water input was 1.4 bales. The number of bales produced per irrigation water is heavily dependent on the in-season rainfall and has less meaning in assessing water use efficiency. There was a large variability in farm level irrigation efficiency from 20% to 80% between farms and averaged 57% across the industry. This means on an average about 47% of irrigation water is lost between the point of the pump and the plant leaves. Most of these losses are occurring in storage, conveyance systems and in applications. To achieve higher farm level irrigation efficiencies improvements are required in irrigation infrastructures and better scheduling techniques. However, economics also need to be considered in achieving higher efficiencies.

Table 2. Seasonal ET and water use efficiencies

Season	**96/97**	**97/98**	**98/99**
Seasonal ET mm	760	755	694
CWUE kg/ha/mm	2.49	2.52	2.52
Bales/total water	0.73	0.76	0.88
Bales/irrigation water	1.18	1.19	1.86
Irrigation efficiency	0.54	0.55	0.60

Even though cotton is very efficient in terms of returns per unit water input, these results reveal that there is considerable room to improve production efficiency and quantitative water use efficiency at many places. An integrated water management approach is being developed with the aims of optimising production and quantitative water use efficiencies in cotton farms.

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