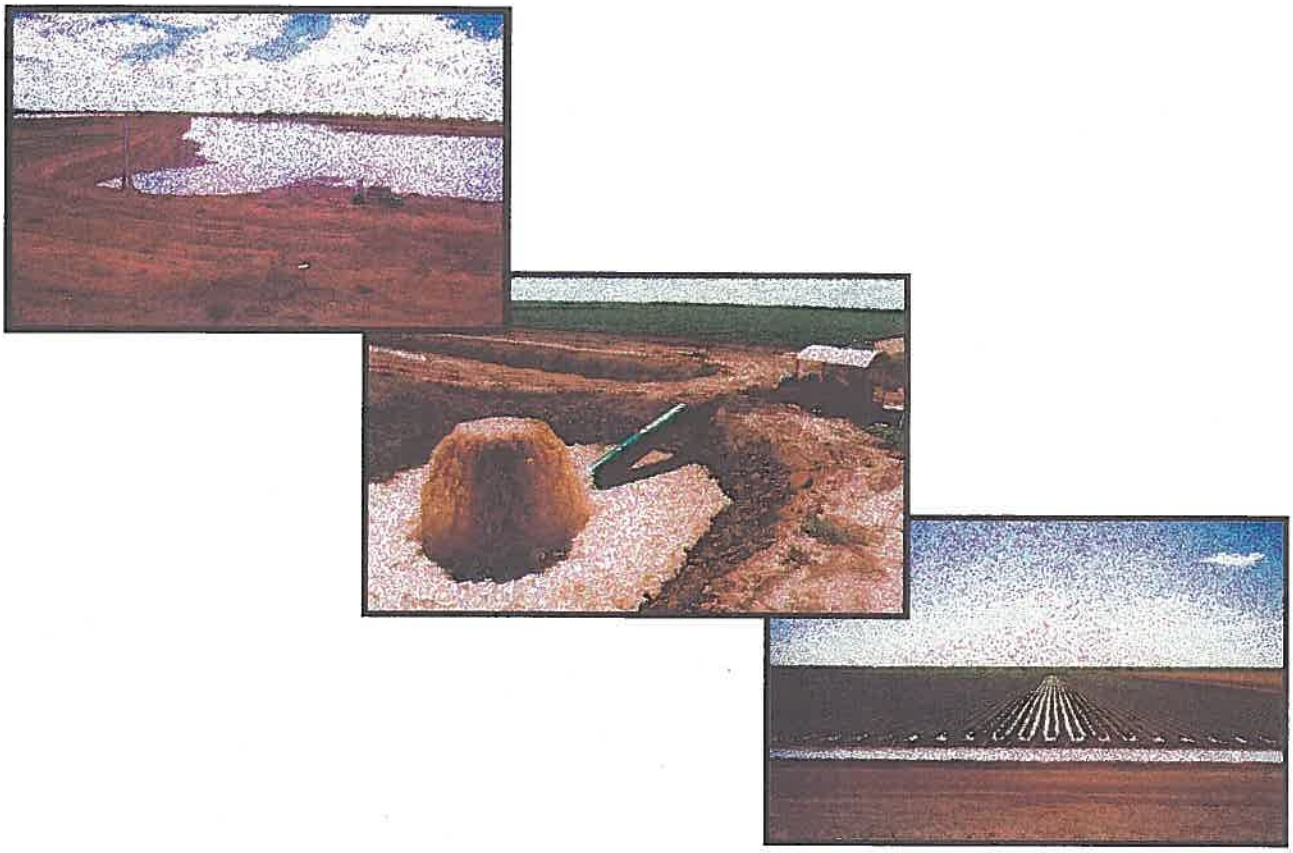
Best Management Practices for Maximising Whole Farm Irrigation Efficiency in the Australian Cotton Industry



Final Report for CRDC project NEC2C

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Plain English Summary

Background

Irrigation is an essential practice for much of the Australian cotton industry. However, the demand for water resources has been increasing due to both the expanding development of competing industries and communities which are reliant on water and the requirements for environmental flows. Efficient use of the water resource is necessary to demonstrate that the industry is managing the resource in an economically and environmentally sustainable manner. Improvements in water use efficiency may also enable increases in production without increasing water consumption.

The Cotton Research and Development Corporation commissioned this project with the aim of identifying the potential for improving water use efficiency on surface irrigated cotton farms in Australia. This was expected to be achieved through (a) reviewing previous research within the cotton industry and whole farm irrigation efficiency literature, (b) measuring and benchmarking whole farm irrigation efficiency on commercial irrigated cotton farms, (c) investigating alternative management and design practices to improve whole farm irrigation efficiency and (d) creating an awareness of opportunities to improve whole farm irrigation efficiency through workshops and field days in the major cotton growing areas. The project was conducted by the National Centre for Engineering in Agriculture (NCEA) in conjunction with the Queensland Department of Natural Resources and Mines (DNRM) and the University of Southern Queensland (USQ). Operational support in the final years of the project was provided by Dalton Consulting Pty Ltd.

Key Research Outcomes

- The review of previous irrigated cotton research identified that there was only limited data available on the water use efficiency and performance of surface irrigated cotton in Australia.
- This project physically measured the performance of each component of the whole farm water system under commercial operating conditions. This was an industry first which involved the development and refinement of a range of monitoring technologies resulting in the development of a new industry "standard" for the evaluation of whole farm water use efficiency.
- Measured whole farm water use efficiencies were found to range between 21 & 65% (ie. for every megalitre of water delivered to the farm, only 0.21 to 0.65 megalitres were utilised by the crop).
- Major sources of water loss were identified in both the storage (efficiency = 50-85%) and in-field application (efficiency = 70-88%) systems.
- Significant in-field deep drainage losses (11-30% over season) were measured for surface irrigation conducted under a range of conditions.
- Waterlogging of crops by surface irrigation was identified as a major potential source of yield reduction. Opportunities to significantly increase crop water use efficiency and yields (up to 20%) by reducing waterlogging could be achieved with relatively minor surface irrigation management changes.
- Strategies to improve efficiency should be farm specific but should focus on a mix of both design and management improvements. Realistic potential benefits include: 20-50% reduction in evaporation from storages, 10-15% reduction in the water applied per hectare to fields due to reductions in deep drainage. There is also a potential to increase plant yields per unit water by up to 20% through a reduction in waterlogging associated with irrigation events and better crop water use efficiency.

Industry Impact

This project has identified that there is a potential to improve the application efficiency of many surface irrigated fields through comparatively minor management changes. The experimental results suggest that 10-15% of the applied water could be saved. If only 10% of the applied water was saved on only half of the surface irrigated land in the industry, this would translate into enough water to irrigate an extra 18000-20000 ha. This would result in an increase in industry production of up to 150000 bales/annum with a gross value of approximately $60M per year.

This project has identified that waterlogging associated with inappropriate surface irrigation practices commonly result in 10 or more days of reduced crop growth each season. Yield benefits of up to 20% have been identified through reductions in irrigation induced waterlogging. The adoption of irrigation management strategies identified in this project is conservatively estimated to result in an industry production increase of 200,000 bales/year with a gross value of $80-100M per annum.

Other project activities demonstrating the industry impact include:

- Information data and outcomes of the project have been presented to over 1000 industry stakeholders including irrigators, researchers, government officers, industry development officers and consultants. Of these, approximately 150 growers and cotton consultants in eight cotton growing valleys have attended a detailed training workshop program on methods to evaluate irrigation performance. Grower awareness of the opportunities to improve water security through water use efficiency improvements has also been raised through 14 grower focused field days and 9 broader industry presentations.
- The measured data for the performance of on-farm water storage reservoirs obtained in this project was instrumental in alerting the Queensland Department of Natural Resources & Mines to the legislative constraints affecting water storage efficiency through high levels of evaporation. This data, and the activities of project staff, were instrumental in convincing both the Department and Minister that the 5 metre referable dam height restriction should be lifted to 8 metres. This change alone has the potential with both new and redevelopment of storages to save some 20-40% of on-farm water in Queensland resulting in production benefits of up to 40,000 bales/year with a gross value of $16-18M per annum.
- This project has collected a range of data and developed several tools which can be used to objectively assess the feasibility of infrastructure options for individual farms including improving water storage, distribution and in-field systems. These tools and data are already being used commercially by five industry consultant groups as well industry extension staff. All of the current cotton water use efficiency Industry Development Officers have been trained to use the whole farm irrigation efficiency evaluation methods developed in this project. Over sixty Irrimate™ devices have been used to evaluate irrigation application efficiencies on over 25 farms in seven cotton producing regions in the 2000/01 cotton season. As a result of this project, irrigation consultants are also now conducting irrigation efficiency evaluations as a commercial service to clients.
- The benefits of this project should continue to accrue for years beyond its funded period. The main delivery mechanism for continued promotion and adoption of project outcomes is through both the Queensland State Government funded Rural Water Use Efficiency Initiative and commercial irrigation consultants. The involvement of fee for service consultants in the delivery of project outcomes recognises the commercial benefits of the project outcomes and provides a solid foundation for continued delivery to the industry of the project benefits. It should be noted that this is perhaps one of the few times that a public sector research and development project has been able to involve irrigation consultants in the delivery of in-field water use efficiency services to their clients.

Recommendations for the Future

This project has demonstrated that the easiest and largest gains to improve whole farm water use efficiency exist within the in-field application systems. These gains are two-fold, namely, the saving of water from deep drainage and tailwater losses, and the potential to increase crop yield through reductions in waterlogging associated with surface irrigation and increased crop water use efficiency. These benefits can be gained through simple changes in irrigation management which do not always require either extensive farm redevelopment or changes to irrigation infrastructure (e.g. conversion to drip or low pressure mobile application system

Key recommendations to assist in the implementation of the results from this report include:

1. Training and Extension Programs:
   Targeted training and extension programs initiated by the cotton industry specifically to encourage the adoption of surface irrigation assessment and improvement programs identified by this and other projects. These programs should be linked with existing private sector engineering and agronomic consultant groups in order to ensure a sustainable delivery path for this information in future.

2. Evaluation of the Agronomic Impacts of Changed Surface Irrigation Management:
   A cross disciplinary research program to confirm the real cost of surface irrigation induced waterlogging losses and the potential to reduce this impact through simple management adjustments.

3. Economic Assessment of Surface Irrigation Systems:
   A critical economic assessment of surface irrigation improvement programs including the adoption of management changes as well as investment in infrastructure changes. This should include detailed analysis of the cost benefit analysis of storage loss mitigation, distribution losses, and optimised in field layouts.

4. Deep Drainage:
   Deep drainage continues to be one of the most significant potential environmental threats to the cotton industry. Research needs to continue in relation to the evaluation of the real economic and environmental impact of this factor across the industry.

5. The Development of Tools to Evaluate Alternative Irrigation Systems:
   Training and assessment protocols need to be developed to assist producers in making informed decisions regarding deployment of alternative irrigation methodologies. These systems need to be assessed against best practice surface systems.

6. Data Collection for Other Regions:
   The data presented in this work has been collected in the Goondiwindi and Border Rivers region. While some additional data for other regions may be collected by the current government funded water use efficiency programs, the industry should consider expanding the on-farm performance data that is collected to ensure a balanced industry perspective.

1. Background to the Project

Water is one of the key resources for industry and economic development in Australia. It is also one of the main inputs required to maximise the production of cotton crops. Due to the rising pressure on the use and allocation of the national water resource (and in particular the Murray Darling Basin) "water use efficiency" is gaining an ever-increasing profile. Water use efficiency typically means different things to different people. However, one common view is that the opportunities for benefit should be maximised through optimal management of the water resource.

Australia consumes 22,185 GL of water annually. Seventy percent (15,502 GL) of the total water used is consumed for agricultural production of which approximately 11.9% (or 1,840 GL) is consumed by the cotton industry. The cotton industry is second only to the horticultural industry in terms of value derived from the water resource (ABS, 2000) returning a farm gate value of approximately $613 per ML consumed. However, the security of water resources is a major factor determining the future of the Australian cotton industry. In general, the water resource "security" is determined by three factors:

- **The weather:** On an industry and indeed individual basis any degree of water resource security is fundamentally difficult in an arid continent with a spatially and temporally variable climate.
- **The political climate:** While industry groups continue to lobby and debate with government and environmental bodies, on an individual basis the political climate is no more predictable or controllable than the meteorological climate.
- **The efficiency of water use on the whole farm:** On an individual and industry basis part of the water security equation lies fairly and squarely in the hands of the water manager or irrigator. Water security can be determined to some degree at the farm scale where some measure of individual control can be exercised. It is important that we do not rely solely on the meteorological or political climates of the day to determine water security. There remains one sure way of ensuring and optimising our individual whole farm water security, and that is to optimise the whole farm water use efficiency. However in order to participate individually in water security it must first be recognised that there is an opportunity to improve the management and efficiency of water use on the whole farm scale.

Water use efficiency is a key measure of an irrigation system and its management. Benefits from highly efficient irrigation systems include: greater whole farm water security, lower operating costs, improved production per megalitre of irrigation water supplied, maximised production during dry years, and improvements in environmental management both on-farm and within the broader catchment. In the context of the Australian cotton industry, increases in water use efficiency can be achieved through limiting irrigation losses within the system of conveyance, storage, distribution and field application of irrigation water.

As competing demands for water resources grow, so too does the need to find solutions for better and more efficient water use and irrigation practices to meet farm, industry, domestic and whole catchment requirements. Only recently has the environment been recognised as a user of water resulting in concerns regarding existing irrigation water allocations. The cotton industry in Australia is seen as a large user of water and consequently is one industry facing pressure due to competing demands for water. Some 80% of cotton grown in Australia is irrigated. Security of irrigation supply determines the level of production and hence the industry has a major interest in the efficient management of the water resource.

Improvements in on-farm water use efficiency have been identified by government, industry, community and water providers as part of a solution to the competing demand for the limited water resource. In the past there has been debate about the level of efficiency of the cotton industry with regards to its water use practices. Most arguments have traditionally been based on perception rather than fact. Hence, there is a need for a system of benchmarking on-farm irrigation efficiencies in the Australian cotton industry, and to better evaluate irrigation design, management and practice options that assist in improving industry benchmarks.

On-farm water is defined as the water that is pumped, captured, distributed and/or stored within the farm gate. Utilisation of recycled and overland flow harvested water is a component of the farm water volume. The following farm water management systems exist on most surface irrigated cotton farms:

- pumping or harvesting of water from river and overland flows (typically low head high volume pumps);
- storage (typically ring tanks);
- on-farm distribution (typically trapezoidal earthen channels which include culverts and gated pipes);
- application systems (which includes gated supply pipes to head ditches and/or siphons or pipe through the bank application system); and
- tailwater recycling (typically tail drains and tail water recycling channels and utilising supply harvesting pumps.

Within each of these water management systems there are inputs and outputs, which are either used (and therefore available to the crop) or lost. These water inputs at the various scales within the farm system include:

- allocation water pumped through the farm gate;
- off-allocation water pumped through the farm gate;
- groundwater pumped through the farm gate or used by crops directly from shallow groundwater tables;
- on-farm and overland flow water harvesting;
- tailwater that is re-lifted back into the system;
- water delivered to the storage (which may include all of the above inputs);
- water delivered to the distribution system (which is typically from the storage but may be directly from the above inputs);
- water delivered to head ditches;
- water delivered to the furrow;
- irrigation water delivered to the plant root zone; and
- rainfall.

In order to analyse a water use system and gain a measure of losses and whole farm efficiencies, a whole farm water balance approach is needed. The only water input in the whole farm water balance that is of direct economic benefit to the irrigator is the flow associated with crop evapotranspiration (*ET*). Hence, design and management of the storage, distribution and application systems should be directed at minimising transfer losses and maximising the volume available for transpiration.

This project was initiated by the cotton industry to put real numbers on the whole farm water balance of surface irrigated cotton systems such that irrigation efficiencies could be confidently stated. The project was also required to develop a process of whole farm irrigation efficiency benchmarking to enable the identification of opportunities for water use efficiency improvement.

2. Project Objectives and Achievement

2.1 Phase 1 - Measurement Techniques and the Identification of Opportunities in Irrigation Management

- **Collation of past and present water use efficiency and irrigation management research findings**
- **Identify issues and opportunities to improve the current technologies, agronomic and management practices, decision support systems and extension materials at the farm level**
- **Development of farmer friendly irrigation monitoring tools appropriate for whole farm assessments**

An extensive review of whole farm water use efficiency research findings (Section 3) was undertaken. Components of this review have been incorporated into several subsequent documents (see Section 11: Publications arising from the project) as well incorporated into the training program conducted for the industry development officers appointed under the Rural Water Use Efficiency Initiative. Discussions with cotton irrigators throughout QLD and NSW identified a number of issues which had not been adequately addressed in the earlier research including: (a) concerns over the unquantified but potentially significant volumes of water being lost through either evaporation or deep drainage in the various components of the on-farm irrigation system, (b) uncertainty regarding the potential to reduce system inefficiencies through either design or management options, (c) lack of appropriate monitoring tools and techniques to enable routine assessment of irrigation performance, and (d) lack of publicly available information and decision support resources in relation to irrigation management at the farm and in-field scales.

A range of tools for monitoring water management and infield irrigation performance were developed to address the industry concerns raised. The monitoring systems included:

- **Water storage monitoring stations** – including water level sensor, weather station, evaporation monitoring and inflow and outflow meters
- **Distribution channel monitoring systems** – including channel level sensors and inflow and outflow sensors
- **In-field application monitoring system for furrow irrigations** – including siphon flow meters, tailwater flow meters and soil moisture monitoring sensors. Further to this the Irrimate™ system of in-field irrigation efficiency evaluation and simulation was developed for a quick and accurate assessment of in-field irrigation application efficiency. The Irrimate™ and SIRMOD system of surface irrigation efficiency evaluation were also developed and seen as a flagship of this project.

The tools and techniques developed were presented to growers and industry during the series of "*Measure it to manage it*" workshops held in several cotton growing valleys (see Table 1). In-field evaluation methods included the measurement of field volume balances and efficiencies using both the bucket and stopwatch and the head/discharge methods of siphon flow estimation. The use of local evaporation data and dam water level monitoring was used to simplify the estimation of water storage efficiency. The use of whole farm water use data including soil moisture probe data was also used to assess whole farm water use efficiency. These tools were also effective in achieving the other project objectives discussed further below.

2.2 Phase 2 - Benchmarking the Engineering Aspects of Irrigation Performance

- **Development of a uniform approach to measurement and calculation of water use efficiency**
- **Quantification of the various components of the whole farm water balance**
- **Benchmark irrigation performance of the various engineering components of farm water management systems**

This project collaborated closely with the NPIRD (LWRRDC) project to identify consistent and uniform definitions for water use efficiency and to promote those approaches within the industry. The uniform approach to defining and report the water use efficiency and water use efficiency indices at each scale within the farm water balance parameters has been reported in various publications (see Section 11: Publications arising from the project) and promoted within the industry through training and field day activities (see table 1).

The whole farm irrigation efficiency of seven cotton farms in the McIntyre Valley were monitored over the three years of the project. Whole farm irrigation efficiency was quantified on a volumetric (or "engineering") basis which included both the use and loss water balance components of water storages, distribution channels and in-field furrow application systems (i.e. flows, soil moisture, drainage, seepage, evaporation tailwater and crop water use). Data is presented from four water storages, six farm water distribution channels and eleven fields in this report.

2.3 Phase 3 - Best Management Practices to Improve On-Farm Water Use Efficiency

- **Identification of alternative management practices to improve water use efficiency**
- **Field validation of benefits associated with identified management practices**
- **Development of guidelines for Best Management Practice**

The review of current and alternative irrigation management practices highlighted where irrigation efficiency could be improved in water storage, distribution channel, in-field application and therefore, whole farm systems. The largest opportunities were identified in evaporation and seepage mitigation measures in storages, in-field irrigation efficiency (including deep drainage and tailwater reduction) and yield optimisation measures.

A range of alternative management practices were validated in the field during the project. At the storage level, investigations focused on reducing evaporation losses by reducing the surface area to volume ratio (ie deepening) of the storages. A further project to investigate the use of surface covers to mitigate evaporation from storages was initiated out of this project and is currently utilising the storage monitoring stations and evaluation procedures developed in this project. Validations of the alternative infield surface irrigation practices focused on modifications to the inflow rate (ie siphon size & head) and the siphon pull time. Opportunities to improve performance through alternative field design and layout were also investigated using SIRMOD modeling.

This project has played (and continues to play) an integral role in the development of the Irrigation Best Management Practice guidelines being formulated by Cotton Australia as part of the Rural Water Use Efficiency Initiative program. The best management practices identified in this project (either through the review or field validation) form a significant part of the current draft "Land and Water Management" module for the Cotton BMP Manual. In particular the "Objective 4 – Good Water Management" has been firmly underpinned by the outcomes of this project.

2.4 Phase 4 - Extension

- **Increase the awareness of factors influencing irrigation performance within the cotton industry**
- **Encourage adoption of whole farm irrigation monitoring by irrigators**
- **Encourage the adoption of identified Best Management Practices by cotton irrigators**

This project has played a major role in raising the industry awareness of the factors influencing irrigation performance. Information, data and outcomes of the project have been presented to over 1000 industry stakeholders (Tables 1 & 2) including irrigators, researchers, government officers, industry development officers and consultants. Of these, approximately 150 growers and cotton consultants in eight cotton growing valleys in Queensland and New South Wales have attended a detailed training workshop program on methods to evaluate irrigation performance. Grower awareness of the opportunities to improve water security through water use efficiency improvements has also been raised

The staff and resources associated with this project have been heavily involved in the initiation of the cotton component of the Rural Water Use Efficiency Initiative (operated by Cotton Australia and CRC/QDPI) as well as in the training of staff and the acquisition of appropriate monitoring equipment and resources. This support continued through assistance with the establishment of trial sites and the dissemination of information via field days and grower workshops. A similar function has been undertaken in supporting the New South Wales water use efficiency program (operated by NSWAg).

This project has played a significant role in the development and promotion of best management practices for water management in the cotton industry. The project has provided expertise and data for the development of the draft irrigation BMP and played a leadership role in developing a coordinated approach to the water use efficiency extension and adoption programs in both Queensland and New South Wales. Tables 1 & 2 provide an overview of the major extension activities undertaken by the project to raise awareness of water use efficiency issues and encourage adoption of appropriate practices.

Table 1: Grower based presentations undertaken by project staff

Date	Location	Event	Attendees	Aim	Comments
March 1999	Goondiwindi – (Yambacully –Peter Cross/Peter Corrish, Korolea – Rob Newell)	Waterworks CGA field day	250	General awareness of project, equipment being used on farm to measure irrigation efficiency and initial results	
Dec 1999	Goondiwindi (Town)		5 owners, managers and irrigators	Purposely run as a small meeting of key growers to do a "reality check" on results of storage, distribution, application and whole farm efficiency	Irrigators not surprised at the range of high to low efficiencies
April 2000	Goondiwindi (Ray Christie)	Irrigation Efficiency focus group meeting	10 growers, 5 WUE IDO's	Invited to speak at an area wide management meeting and provide a focus on WUE for the new WUE IDO in Goondiwindi employed under the Cotton Aust/QDPI RWUE Initiative	Outcome of the meeting was that the area wide group would also focus on WUE issues and information sharing
May 2000	Pampas (Neal Pfeffer)	Introduction to WUE	10 growers	Invited to speak at grower group meeting and provide a focus on WUE for the new WUE IDO in Dalby employed under the Cotton Aust/CRC/DPI RWUE project	
August 2000	McKenzie River	Measure it to manage it workshop	20 growers	First measure it to manage it workshop assisting John Okello with extension work in Emerald.	Measure to manage was initiated to help understand how much water is being applied to a field compared with the requirement (deficit) and therefore assess efficiency
August 2000	Emerald (Noel Brosnan)	Measure it to manage it workshop	15 growers & cotton consultants		
August 2000	Emerald	Measure it to manage it workshop	15 growers and cotton consultants		
August 2000	Theodore	Measure it to manage it workshop	10 growers		
Sept 2000	St George	Irrigation scheduling and monitoring field day	70 growers and industry reps	Tie in the need for irrigation application monitoring with irrigation scheduling	
Sept 2000	Pampas	Measure it to manage it workshop	15 growers and cotton consultants		
Sept 2000	McAlister	Measure it to manage it workshop	15 growers and cotton consultants		
November 2000	Trangie	Surface Irrigation Evaluation Field Day	120 growers and industry reps	Collaborate with NSW Ag on the need for irrigation efficiency evaluations to prove efficiency	
November 2000	Moree	Measure it to manage it workshop	20 growers and cotton consultants		
February 2001	Gunnedah	Measure it to manage it workshop	30 growers and cotton consultants		

Table 2: Broader industry presentations made by project staff

Date	Location	Event	Attendees	Aim	Comments
April 1998	Narrabri	Industry extension officers workshop	50	General awareness of project – form a partnership with extension team to raise awareness and profile of WUE	
Dec 1998	Narrabri	Farming systems and soils forum	50	Disseminate results within technical profession and growers	
Oct 1999	Toowoomba	Water Balance workshop	30	Workshop water balance research needs in CRDC	Strategies towards research needs
March 2000 to April 2001	Toowoomba	Core Skills training course	50 WUE IDO's	Training in core skills needed for water use efficiency staff	
Jan 2000	Goondiwindi	Industry IDO introduction	10	Introduce CRDC WUE project and outcomes to newly appointed IDO's in QLD RWUE project	Strategic move in collaborative extension of this project results and findings
Feb 2000	Goondiwindi	Cotton Industry water meeting	20 CRDC reps, IDO's, NSW Ag and QDPI	Introduce CRDC WUE project and outcomes to newly appointed IDO's in QLD RWUE project – extension strategy	Strategic move in collaborative extension of project results and findings
Feb 2000	Dubbo	Industry IDO training	20	Conduct training of NSW AG WUE IDO's	
June 2000	Yamba	Industry extension officers workshop	50	Coordinate Cotton WUE IDOs and form a strategy towards irrigation extension	Strategic move towards running workshops in regions
June 2000	Dalby	QDPI IDO training	15	Train WUE IDOs in whole farm irrigation efficiency assessment including the use of equipment	
August 2000	Brisbane	Australian Cotton Conference	250	Present paper on Whole Farm Water Use Efficiency	
May 2001	Dalby	Cotton week field day tour	300	Presentation on irrigation systems and methods	
July 2001	Toowoomba	IAA Irrigation Conference	250	Present paper on in-field irrigation efficiency optimisation	

3. Review of Past Work

The literature of past work conducted in the area of irrigation and water use efficiency (and not just specifically to cotton) was reviewed with the aim of understanding any previous experimental approach that could be used in this project, summarising any irrigation efficiency data that already exists for the cotton industry, and scoping any potential best management practices that might exist to improve efficiency (including whole farm water loss mechanisms and their mitigation). The review is written under the headings of the three main water management areas of the whole farm cotton system, which include water storages, distribution systems and in-field application systems. A review of any whole farm data was also included.

3.1 Whole Farm Irrigation Efficiency

Perhaps the most comprehensive and only significant study on broader industry and whole farm irrigation performance was that undertaken by Cameron Agriculture (& A B Hearn) (1997). They quantified industry irrigation performance through a process of valley and individual farm data review (including crop yield, water meter, water provider and soil moisture data). Efficiency of irrigation was defined in two components: the engineering (or volumetric) efficiency (or irrigation efficiency IE) and the agronomic efficiency (or crop water use efficiency (CWUE).

On the three individual farms that were reviewed IE averaged 75%. However the overall mean for regional data was 58% IE with individual regions in the range of 41% for the McIntyre valley and Emerald to 94% in the Gwydir valley. The mean for individual farms in these regions was 63% ranging from 49 to 78% IE.

3.2 On-farm Water Storage and Distribution Systems

The major system losses in open farm water storage and distribution systems, which occur on a continuous basis, are evaporation and seepage. The major factors affecting the performance of storage and distribution systems include the local evaporation potential, soil percolation rates and the dam or channel design parameters. The other notable storage and distribution inefficiencies include inaccessible storage volumes (due to poor design) and storage failures. Inaccessible storage and distribution volumes typically occur when the outlet point is not at the lowest point of dam or channel.

The storage and distribution of on-farm water may represent a considerable component within the whole farm water management system. For example, the cotton industry relies heavily on off-allocation and overland flow harvested water and hence, requires a substantial capacity to store and distribute water around the farm. Hence, a typically irrigated cotton farm requires a large ring tank reservoir (2-7 m high and many hectares in area) to ensure a reasonable security of water supply for irrigated production with distribution via large earthen channels. However, in other regions or industries with more secure water supplies, storage structures are less common and if present typically much smaller in size. On-farm distribution in these cases is also more likely to be via pressurised pipe systems.

Storage failures are commonly attributed to inadequate site investigation, lack of construction material soil testing and poor construction quality control. Storages can fail without warning and the reasons are commonly only apparent to irrigators after the failure. There is currently very little regulation of how farm storages are built in Queensland. Dams with embankments greater than 5m have been classified as referable and therefore require some degree of review and approval by the Department of Natural Resources. Recent Queensland Rural Adjustment Authority Development Incentive Schemes (QRAA-DIS) for water storages have also attempted to ensure that water storages and farm irrigation schemes are developed according to current best practice. Many dams have historically been constructed with very little regulation of hydrologic design, geotechnical investigation or construction supervision/quality control.

Pump and pipe inefficiencies are typically design-related problems in which the equipment is not sized properly to meet the demands of the irrigated production enterprise. Other inefficiencies in this area can also be attributed to poor maintenance of pump and pipe condition.

3.2.1 Performance evaluation

The major system losses in open farm water storage and distribution systems are evaporation and seepage. These losses occur on a continual basis and depending on the local evaporation potential, soil types and design parameters these losses may be as high as 50% of total water available. Both seepage and evaporation are flux loss mechanisms. Hence, the total volume lost is a function of both the loss rate (typically mm/area/day) and the total area subjected to this loss. For example, farm seepage and evaporation losses are typically estimated from a knowledge of the evaporation and seepage flux rates, a knowledge of the storage and channel areas, and the opportunity time for seepage and evaporation (i.e. period of storage or distribution).

Evaporation Monitoring

The traditional approach for monitoring the evaporation losses from a free water surface such as a water storage or distribution channel is to use a standard evaporation monitoring pan (or evaporimeter) and relate evaporation from the pan to free water surface evaporation via a coefficient. The commonly used standard evaporimeter is the U.S. Class A evaporation pan Another common evaporimeter is the Australian sunken tank which is similar but it sunken into the ground so that the water surface is at the same level as the ground. Another common method of estimating evaporation from a free water surface is to use Horton and Jobling's (1984) relationship which indicates that evaporation from a free water surface (i.e. Penmans "Open Water Evaporation") is approximately equal to 0.8 times the evaporation from a U.S. Class A evaporation pan. However, Watts and Hancock (1985) suggest that another practical approach to estimating evaporation could be to use an energy balance approach and one of the physically based "combination" formula involving a combination of the radiation and aerodynamic terms. This method has been used to calculate evaporation using global and nett radiation sensing and typical weather station data.

Seepage Monitoring

Bosman (1993) developed a method to discriminate between evaporation and seepage losses from open water canals was developed under controlled conditions and applied to standing water in two blocked-off concrete-lined canal compartments having sealed and unsealed joint treatments respectively. Evaporation loss from both compartments averaged 11% monthly. Seepage loss ranged from 1% to 30%, on average, for sealed and unsealed compartments respectively.

Taniguchi *et al.* (1993) developed an automatic seepage meter using a heat pulse method was developed to obtain continuous measurement of ground-water seepage rates. According to calibrations of the automatic seepage meter fitted with a 50 cm diameter collection funnel, seepage rates from $2\times10_5$ to $5\times10_4$ cm/s can be obtained by measuring the time when the temperatures as measured by thermistor peaks after applying a heat pulse. The automatic seepage meter was used to measure continuous seepage rates into Lake Biwa, Japan. The ground-water seepage rate measured by the automatic seepage meter in Lake Biwa changed by six times within 12 hours. The automatic seepage meter is useful for surface-ground-water studies, because a continuous seepage rate can be obtained without errors caused by the resistance of a collection bag to water flow.

3.2.2 Strategies to improve performance

3.2.2.1 Evaporation losses and mitigation

Evaporation losses have been estimated (Sainty, 1996) to be as high as 50% of the stored water for typical ring tank storages in the cotton industry. The cost of evaporation losses alone under these conditions has been estimated to be worth ~$200,000 for a typical cotton farm (Sainty, 1996) and in excess of $50M per annum for the Gwydir Valley alone (Condie and Webster, 1995). Hence, evaporation losses from on-farm storages are likely to represent a significant source of volumetric inefficiency and economic loss in those industries (e.g. cotton, sugar) where storages are prevalent.

The evaporation potential of the earth's atmosphere is a physical phenomenon, which cannot be modified at the gross level. However, evaporation shielding or mitigating the evaporation potential at the water's surface does present some options for evaporation control. Evaporation is most significantly affected by wind speed and surface area suggesting that the modification of these variables would provide the greatest opportunities for evaporation control.

Wind Breaks

Crow and Manges (1967) found that evaporation from a water surface decreased as the ratio of baffle separation to baffle height decreased. When this ratio was greater than 50 no effect was noticed. At a ratio of 16 a 9% reduction in evaporation was noticed. Linacre *et al.* (1970) showed that vegetation density of windbreaks and surface water plants (e.g. swamp reeds) had a significant on modifying the water surface microclimate and thus reducing evaporation.

Condie and Webster (1995) undertook computer modelling of evaporation and reduction techniques and showed:

- Evaporation increases substantially with wind speed. An example of increasing windspeed from 4km/hr to 18 km/hr produced double the evaporation.
- The depth of the water storage had almost no effect on the evaporation per unit area. An example of increasing depth from 1.0m to 6.0m reduced evaporation by less than 1% per unit area.
- Turbidity and sediment load had no effect on evaporation.

Consequently they modelled the effects of windbreaks and showed that windbreak baffles (including trees) can reduce evaporation by up to 20%. They found that it was generally agreed among farmers that trees planted as wind breaks along existing storage embankments would increase the risk of embankment failure. Hence a system of purpose built internal embankments with tree shelters was modelled with daily cycles of air movement typical to that of Narrabri in northern NSW. At moderate wind speeds of 11 km/hr evaporation was reduced by 20% from 7.5 mm/day to 5.9 mm/day. The suggestion for windbreak design was that rows should be placed at right angles to the predominant prevailing winds and at a spacing of approximately ten tree heights.

Storage Design

The effect of increasing the volume to surface area ratio by deepening storages has some potential to reduce evaporation losses by reducing surface area and the temperature of water (Condie and Webster, 1995). Storages in the sugar, dairy, horticulture and cotton industries are typically 2 to 7 metres in depth and present considerable scope for deeper storages. However, Condie and Webster (1995) identified that the main barriers to adopting increased storage depth were the perceived increased risk of storage failure and the increased costs of earthworks. However, an example was presented that suggested that the additional cost for a 500ML ring tank at 6m deep rather than 3m deep would be recovered through reduced evaporation in a period of 3-4 years. Such a measure would effectively reduce surface area by 50% and therefore reduce total evaporation by a similar amount. This recovery period would be dependant on the value of water (due to lost production) and not the cost of the water. Where areas are land limited the cost recovery equation might also include land area and potential increased production area savings.

Multiple Cells

Condie and Webster (1995) also found that the exchange of water between a number of storages or cells within a storage would minimise the surface area of water exposed to evaporative losses and therefore a simple method for reducing evaporation. As in the case of deepening storages the cost recovery period of incorporating multiple cells was calculated at 3-4 years.

Floating Materials

Condie and Webster (1995) of the CSIRO Centre for Environmental Mechanics (CEM) undertook a review of methods for reducing evaporation for large storages. Suspended floating materials have the dual effect of reflecting the incident solar radiation and reducing the water surface area and exposure to wind. The materials need to be durable and resistant to the elements encountered in the storages. Jones (1992 cited in Condie and Webster, 1995) found that monomolecular films on the surface of water reduced evaporation by 20-60% in laboratory scale trials. However in large scale dams practical limitations due to wind and waves were recognised. Condie and Webster (1995) subsequently identified a range of materials which had been used for evaporation control with variable effect (Table 3). Their suggestion is that a suitably cost effective material would both reduce evaporation by a significant percentage and have a long enough life to enable full cost recovery due to reduced evaporation. Polystyrene would not be expected to last more than 10 years. Floating lightweight concrete was presented as a long life low cost option that may need to be explored further.

Burston and Akbarzadeh (1995) studied the effect of floating plastic rings on the surface of pools of water in reducing evaporation. Treatments included open plastic rings, plastic rings with aquatic plants in the middle, and plastic rings covered with white painted bubble plastic. Only laboratory scale work was undertaken however this type of evaporation mitigation method showed some promise. Results of the different treatments were:

- Open rings – 0.4% evaporation reduction
- Floating aquatic plants in the middle of the rings – 5.5% evaporation reduction
- Rings covered with white painted bubble plastic – 65% evaporation reduction

At a field scale the cost of such a method would be prohibitive unless the material could be produced at a low enough cost and high enough life span to make cost recovery achievable within a short time period. Adcock (1995) also undertook experiments to determine the evaporation reduction effect of floating plants with 25%, 50%, 75% and 100% water surface cover. However, over a three-month period none of the treatments showed any evaporation reduction potential.

Table 3: Suspended materials for evaporation control *(after Condie and Webster, 1995)*

Material	Evaporation Reduction (%)	Reference
Lily Pads	16	Cooley and Idso (1980)
Polystyrene Beads	39	Myers and Frasier (1970)
Wax Blocks	64	Cooley and Myers (1973)
White Butyl Rubber	77	Cooley (1970)
White Plastic Spheres	78	Crow and Manges (1967)
Continuous Wax	87	Cooley and Myers (1973)
Suspended Plastic Sheeting	90	Drew (1972)
Foamed Rubber	90	Dedrick *et al.*, (1973)
Polystyrene Rafts	95	Cluff (1972)

Farmer awareness of evaporation losses is typically high in the cotton industry (Sainty, 1996) but unknown in other industry sectors. The adoption of smaller storage cells and deeper storages to minimise evaporation in the cotton sector has also occurred to a limited extent suggesting that these options are more attractive to irrigators. However, adoption of other strategies to reduce evaporation is typically low in all sectors.

The cost effectiveness and appropriateness of the alternative strategies has generally not been investigated. To estimate the cost effectiveness of a method, the rate or percentage of water saving and the dollar value of the water need to be known. Note that the cost of the water is not necessarily (and rarely) the same as the value of the water. For example, the value of the water may be significantly greater than its cost due to the value of the crop, which could be potentially, be produced with the water.

3.2.2.2 Minimising storage failures

Storage failures typically occur due to either hydrologic failure and/or physical embankment failure. Anecdotal evidence suggests that an estimated 20-30% of dam embankments fail (Barrett, Purcell and Associates, 1998) due to either poor design, site investigation, construction, construction supervision and/or maintenance. Recommendations of best practice design, site investigation, construction and maintenance are given in this document.

3.2.2.3 Seepage losses and mitigation

Seepage is simply defined as the loss of water due to infiltration through the bed or banks of an irrigation channel or dam. Seepage losses have presented considerable problems in many farm storages and distribution channel networks. It has been suggested that conveyance and application losses should not be higher than 15% in properly designed irrigation schemes (Ait Kadi, 1993 in Kirda and Kanber, 1999).

Seepage Rates

Burt (1995) presented seepages rates (Table 4) depending on soil type for unlined channels (taken from Withers and Vipond, 1980) for relative comparison purposes only. Canal seepage rates for a range of soil textures were also reported by Worstell (1976). Average seepage rates ranged from 0.06 to 0.6 m^3/m^2/day depending on soil type with the majority of rates less than 0.3 m^3/m^2/day.

Table 4: Approximate channel seepage losses *(from Burt, 1995)*

Type of soil	Seepage Loss (m^3/m^2/day)
Impervious clay loam	0.07 – 0.10
Clay loam, silty loam	0.15 – 0.23
Clay loam with gravel, sandy clay loam	0.23 – 0.30
Sandy loam	0.30 – 0.45
Sandy soil	0.45 – 0.55
Sandy soil with gravel	0.55 – 0.75

McLeod *et al.* (1994a) conducted seepage measurements at two channel sites in Sheparton Region of the Goulbum-Murray Irrigation District in northern Victoria. They measured seepage rates between 14 and 34 mm/day in the Tatura East channel and 5 and 9 mm/day at the Dhurringile channel operating under normal operating conditions. Analysis of the influence of sub-surface hydrological conditions on the seepage loss rate of the channel indicated that the net available head (defined as the difference between the channel water level and the groundwater elevation in the bores close to the channel) to drive seepage flow from the channel was the most significant factor in determining the seepage loss rate from a channel.

Further the related problem of leakage from irrigation channels was highlighted in this study in the Dhurringile channel. Differentiation between seepage and leakage was implied as being between 5 and 19 mm/day. The primary cause of the leakage process was attributed to the presence of the yabbie (*Cherax destructor*).

Mitigation of Seepage

According to the report Water and the Australian Economy a joint study of the ATSE and IEAust (1999), massive improvements in rural water use efficiency are needed to supply economic uses and the environment in the areas of on farm water use and improved distribution systems efficiency, including the hydraulic upgrade of existing channels and through improved river management. More research on increasing the efficiency of water distribution including more efficient techniques of application, irrigation benchmarking, distribution system design and quality control. They also recognise a great need for much improved research effort on stormwater systems.

Smith (1973) conducted seepage analysis of irrigation distribution channels. He found that de-silting of an irrigation channel had no effect on the seepage rate. As an additional component to the work of McLeod *et al.* (1994a), McLeod *et al.* (1994b) calibrated and validated a channel seepage model. Using this model they investigated the effects of desilting the channel and the influence of water quality and temperature changes of the water. They also found that de-silting had no effect on seepage rate. This was also true in the case of water quality. In the case of water temperature Dillon (1984) and Duke (1992) has found that increases in water temperature have significant effects of increasing the conductivity and therefore the seepage rates in channels. McLeod *et al.* (1994b) however found no significant effect of water temperature on seepage rate in the modelling exercise. Some model parameter co-dependence was seen as the reason for this unusual result.

Burt (1995) highlights the importance of proper soil compaction at the optimum moisture content as a construction parameter that will almost eliminate seepage. He emphasises the fact that adequate storage design typically includes a well-controlled compaction process however that this does not always occur during channel construction. Given the volumes and opportunity time of water losses from channels over an irrigation season it is recommended that the costs of compaction of distribution channels would be quickly offset through water savings.

Ragusa and De Zoysa (1991) investigated the effect of bethnic algae in reducing the seepage from unlined channels. They found that the introduction of the polysaccharide producing algae was correlated to the reduction of the hydraulic conductivity of the channel. Hydraulic conductivity also decreased with increasing algal and bacteria numbers.

3.3 In-Field Application Systems

The ability of the irrigation system to apply water uniformly and efficiently to the irrigated area is a major factor influencing the agronomic and economic viability of the production system. The performance evaluation of in-field application systems can be divided into the two major components of water losses and uniformity of application. Although both components are influenced by system design and management practices, the losses are predominantly a function of management while the uniformity is predominantly a function of the system design characteristics (Solomon, 1993). However, the irrigation system is not usually expected to supply all of the moisture required for crop production as some of the crop's water requirements may be met by pre-season moisture stored in the soil profile, rainfall during the growing season, or from shallow groundwater tables. Hence, optimal irrigation management requires not only a knowledge of the characteristics of the application system but an understanding of the environment in which it operates.

The major sources of water loss by in-field application systems are due to evaporation (from either the atmosphere, free water surface or soil surface), deep drainage or by surface run-off. The dominant loss mechanism is closely related to the method of application but in all cases may be substantially reduced by the adoption of appropriate management practices. Typical application efficiencies (Table 5) for the most common irrigation systems indicate that higher efficiencies can normally be expected through the use of micro-irrigation or low pressure overhead spray systems.

However, substantial water losses are often found where these systems are being used with inappropriate management practices (e.g. excessive watering periods, irrigating in high wind). In most cases, the potential distribution uniformity in a well-designed and maintained application system is greater than 85% (Table 6).

Table 5: Typical efficiencies for irrigation application systems
(after Solomon, 1993)

Type of system	Application efficiencies (%)
Surface Irrigation	
Basin	80-90
Border	70-85
Furrow	60-75
Sprinkler Irrigation	
Hand move or portable	65-75
Travelling gun	60-70
Centre pivot & Linear move	75-90
Solid set or Permanent	70-80
Micro-irrigation	
With point source emitters	75-90
With line source emitters	70-85

Table 6: Irrigation systems and potential whole field distribution uniformities *(from Burt, 1995)*

Irrigation System	Potential Field DU (%)
Permanent under tree sprinkler	94
Linear move	92
Orchard drip	90
Sloping furrows	89
Level furrows	87
Border strip	85
Row crop drip	90
Hand move sprinkler (w alt. sets)	85
Hand move sprinkler (w/o alt. sets)	75

Surface irrigation (predominantly border and furrow in Australia) is the dominant method of applying water to pastures and to a wide range of field and row crops. It accounts for in excess of 70% of the irrigation water in Australian and generates more than $4.5Billion in Australian gross products annually. The efficiency of surface irrigation is a function of the field design, infiltration characteristics of the soil, and irrigation management practices (Hanson *et al.*, 1993; Raine *et al.*, 1998). While it is often claimed that the application efficiency of well designed and managed surface irrigated cotton is over 80% (Anthony 1995), there is little published evidence to confirm the widespread existence of these efficiency levels on commercial farms. Relatively high efficiencies (>80%) are possible for surface irrigation under experimental conditions where the levels of management and control are high. However, efficiencies achieved on-farm under commercial conditions are sometimes low and certainly highly variable. For example, Elliott and Walker (1982) reported efficiencies in the order of 50-70% for surface irrigation in Colorado while Smith (1988) observed efficiencies of 30-50% on one cotton farm and 40-80% for several vineyards on relatively light soils in the Riverland of southern Australia. Raine and Bakker (1996a&b) also found that seasonal application efficiencies of surface irrigated sugarcane in the Burdekin region typically ranged between 30 and 60% with the efficiency of individual irrigations ranging between 10% and 90%.

Yule (1984) conducted water balance measurements at Emerald in 1982/83 and 1983/84 and found that irrigation application was generally 70 to 90% efficient. They trialed different irrigation frequencies based on predicted deficits. Water balance data for this work is shown in Table 7. In general the amount of total runoff was determined by the period of runoff. Deep drainage was assumed to be non-existent due to the fact that the applied irrigation minus the runoff (i.e. total infiltration) was less than then predicted deficit.

The soils in these trials had a clay content of 70% which Hearn (1998) states are self-regulating for furrow irrigation. Final infiltration rates of the order of 2mm/hr were measured in these trials indicating a potential for deep drainage if irrigations were not managed well. It should be noted that the deficit was predicted in this data and not physically measured and that the experimental plots did not represent the dimensions of a typical commercial cotton production system.

Table 7: Water balance data from Yule and Keefer (1984)

Predicted Deficit (mm)	Irrigation Applied (mm)	Total Runoff (mm)	Application Efficiency
51 (av.)	49		74%
75 (av.)	70		88%
107 (av.)	92		87%
140 (av.)	126		89%
44 (indiv.)	54	13	76%
73 (indiv.)	76	9	88%
146 (indiv.)	162	22	86%

Table 8: Components of the soil water balance measured by Douglas et al. (1996) during the 1995-96 season at ACRI.

	Irrigation (mm)	Runoff (mm)	Et (mm)	Deep Drainage (mm)	Soil Storage (mm)	Efficiency (%)
Irrigation 1	95					
Irrigation 2	94	2.4	22.9	2.04	65.1	95%
Irrigation 3	82	6.4	10	1.02	55.9	90%

Douglas et al. (1996) measured the water balance of an irrigated cotton system at the Australian Cotton Research Institute near Narrabri in NSW on a grey cracking clay soil (60% clay) with 200m furrows and 1:1176 slope. The results of three irrigations are presented in Table 8. This data shows high efficiency of irrigation application. However it should be noted that these measurements were under controlled conditions on relatively small field lengths.

3.3.1 Performance evaluation

The performance evaluation of surface irrigation involves an assessment of both the volume and uniformity of the water stored within the root zone. Factors affecting surface irrigation performance include furrow inflow rate, the soil infiltration characteristic, field slope and length, surface roughness and furrow geometry. Some of these parameters are partially dependent on other factors (e.g. infiltration rate varies with inflow and furrow geometry) while the measurement of most of these parameters (particularly infiltration, roughness and geometry) involves a high degree of uncertainty due to spatial variation. A comprehensive coverage of equipment and techniques involved in the evaluation of surface irrigation is given in Walker and Skogerboe (1987).

The soil infiltration characteristic is one of the dominant factors affecting surface irrigation performance and exerts its influence by controlling the rate of advance of irrigation water down the furrow or bay. A knowledge of the spatial average value of this characteristic is required for the optimisation of surface irrigation. However, real-time control and optimisation of individual irrigations requires an ability to also measure the infiltration characteristic during the irrigation event. Conventional methods of measuring infiltration rates include point techniques (i.e. disk permeameters, ring infiltrometers), area techniques (e.g. blocked furrow infiltrometers, inflow-outflow measurements, flowing furrow infiltrometers) and real-time techniques (e.g. using irrigation advance data in volume balance equations).

Point measurements of infiltration rates are rarely satisfactory for the evaluation of infiltration under surface irrigation and do not normally produce a satisfactory simulation of actual furrow advance nor an accurate prediction of tailwater volumes (Elliott and Walker, 1982). This may due to differences in infiltration rates that have been found between water flowing in furrows compared and stagnant (i.e. ponded ring, blocked furrow) tests (Bautista and Wallender, 1985). A large number of point measurements are also required to adequately accurately identify the average field infiltration and spatial variability. They are also likely to be unreliable as predictive measures due to temporal variation.

Inflow-outflow methods, in which infiltration rate is calculated as the difference between the measured water inflow and outflow rate from a single furrow, have been found to yield the best estimates of final infiltration rates (Elliott and Walker, 1982). While these techniques have been widely used in research applications, they are time consuming and unlikely to be used by commercial irrigators or consultants. The usefulness of these techniques in predicting irrigation performance is also low due to spatial and temporal variation.

The most effective method of determining infiltration under surface irrigation is to calculate the average infiltration characteristic based on volume balance calculations using the irrigation advance rates, hydraulic cross sections and tail water volumes (Elliott and Walker, 1982). This "real-time" assessment of the infiltration characteristic involves the use of a volume balance equation relating measured irrigation advance data to infiltration. Assumptions inherent in these methods include: uniform infiltration throughout the field, constant furrow inflow rate, slope, roughness, and furrow geometry, and the form of the equations describing the advance distance versus advance time and cumulative infiltration versus opportunity time (Hanson *et al.*, 1993). The most commonly used infiltration characteristic is the modified Kostiakov (also known as the Kostiakov-Lewis) equation:

$$z = kt^a + f_o t$$

Where z is the cumulative infiltration per unit length, t is the opportunity time of infiltration, f_o is the final (or basic) infiltration rate per unit length, and k and a are empirically fitted parameters. The calculation of the infiltration characteristic using field measured inflow rate, advance data, hydraulic cross section data is given in Walker and Skogerboe (1987). Smerdon *et al.* (1988) and Blair *et al.* (1988) evaluated various equations for calculating infiltration using advance data and found that the modified Kostiakov equation described the field observed infiltration best with prediction of advance times and estimates of distribution uniformity within ±5%. However, the modified Kostiakov equation was found to greatly underestimate cumulative infiltration where the advance exponent approached unity.

The use of the modified Kostiakov equation involves either measuring or assuming the final infiltration rate. Both Childs *et al.* (1993) and Raine and Bakker (1996b) used a flow-though infiltrometer to calculate the final infiltration rate and found that the results were comparable with final infiltration rate measured using a neutron probe. More recently, McClymont and Smith (1996) proposed a numerical technique for calculating each parameter in the infiltration characteristic from the advance data.

In each of these techniques, relatively short irrigation times hamper the identification of the final infiltration rate and the magnitude and nature of prediction errors due to spatial trends in infiltration rates is dependent on the direction of the trend relative to the flow direction (Bautista and Wallender, 1993). Published values for final infiltration rates have also been used with only "some loss of accuracy" in the prediction of the infiltration characteristic (Elliott and Walker 1982).

The largest uncertainty in well-calibrated, well-constructed, and properly used flow measurement devices is the measurement of flow depth or head in flumes, weirs, and orifices, or the time reading in volumetric measurements (Trout and Mackey, 1988a; Bos *et al*,. 1984). Inaccuracy inherent in the flow measurement will cause uncertainty in the measured infiltration rates. Hence, inflow-outflow infiltration determination uncertainty increases rapidly as the percent of inflow that is infiltrated decreases (Trout and Mackey, 1988b). Furrow flow measurement uncertainty varies with the device and flow rate, but generally exceeds plus or minus 5% and often exceeds plus or minus 10% (Trout and Mackey, 1988a). Therefore, accurate infiltration measurement requires measuring long furrow sections in which much of the flow is infiltrated (Trout and Mackey, 1988b).

Similarly, due to high spatial variability, measuring several furrows is critical to determining the average infiltration rate with confidence (Trout and Mackey, 1988b). Autocorrelograms have been used as a tool to determine the distance between samples required to avoid spatial correlation and thus get the maximum new information regarding infiltration variability from sampling (Bautista and Wallender, 1985). Cross correlograms have also been used to estimate blocked furrow intake from ring infiltration tests (Bautista and Wallender, 1985).

3.3.2 Strategies to improve performance

The efficiency of surface irrigation is a function of the field design, infiltration characteristic of the soil, and the irrigation management practice. Substantial improvements in application efficiency are possible through the adoption of appropriate surface irrigation design and management practices including the use of appropriate furrow lengths, irrigation cut-off times and water application rates (Raine and Bakker, 1996a&b). However, irrigators often find it difficult to identify best management practices due to the complexity of the management parameter interactions and the variability in irrigation performance across soil types and throughout the irrigation season. It has also traditionally been difficult to develop site specific guidelines for field design and management without extensive field experimentation. While the value of field research should not be underestimated, it is expensive and time consuming with results limited to the range of conditions investigated.

Both spatial and temporal variations in the infiltration characteristic are a major physical constraint to achieving higher irrigation application efficiencies (Shafique and Skogerboe, 1983). Seasonal variability in infiltration has been found to vary by a factor of up to four, with particularly dramatic differences in infiltration found between the first and second irrigation events (Elliott *et al.* 1983). Differences in infiltration throughout the season have been attributed to surface sealing, soil moisture content prior to irrigation, and the effect of mulch on flow retardation (Raine *et al.*, 1998). Infiltration has also been found (Raine *et al.*, 1998) to vary by up to 30% between furrows in the same field during an irrigation event.

The variation in infiltration characteristics raises concerns over the adequacy of generalised irrigation design and management practices (Raine *et al.*, 1998). The large spatial and temporal variation in infiltration characteristic suggests that substantial improvements in seasonal efficiency and uniformity could be achieved. For example, Raine *et al.* (1998) found that the use of seasonal average infiltration characteristics to optimise irrigation management practices would increase application efficiencies by 25-30%. However, the application of event specific management practices based on real-time measurement of the infiltration characteristic would have increased application efficiency by a further 22-39% (Raine *et al.*, 1998). In both cases, the effect of the changed management practices on distribution uniformity and root zone storage efficiency would need to be considered before implementation.

Another major obstacle to the adoption of improved management practices at the farm level is the recognition by the irrigator of the benefits associated with implementation. Simulation modelling provides an opportunity to identify more efficient practices and assess the benefits for a fraction of the time and cost of field trials. While irrigation earthworks, water diversion, storage and distribution works are routinely designed in Australia using well defined parameters and models, the surface irrigated field is often poorly designed with little use of either field measured or model data.

A wide range of irrigation design and management tools have been developed to assist irrigation researchers and managers investigate irrigation performance at the catchment (Prajamwong *et al.* 1997) and field scales (Strelkoff 1985, Rayej and Wallender, 1987; Walker and Humphreys, 1983). However, a survey by Maheshwari and Patto (1990) found that most Australian irrigation designers “guess” the design variables, which dominate the performance of surface irrigation. This is of particular concern given the ready availability of simulation software and design manuals. Similarly, few irrigators or extension officers use any form of simulation model or decision support aid to optimise the performance of individual irrigations by selecting flow rates and times to cut-off to maximise performance.

Maheshwari and McMahon (1993) investigated the performance of six border irrigation models, including the Walker (1993) and Strelkoff (1985) models, on over 60 individual irrigation events. It was concluded that the Walker (1993) model was best for predicting advance times and that the Strelkoff (1985) model better at predicting the recession phase. More generally, it was found that the models employing the full hydrodynamic and zero-inertia approaches were the most appropriate with no difference found between the full hydrodynamic and zero-inertia approaches of the Walker (1993) model.

McClymont *et al.* (1996) performed a sensitivity analysis on the Walker model and found that it was able to simulate surface irrigation processes adequately. However, the model does show a tendency to slightly underpredict the rate of advance and the volume infiltrated (Maheshwari and McMahon, 1993; McClymont *et al.*, 1996) which can be removed by an appropriate calibration procedure (Smith *et al.*, 1997). McClymont *et al.* (1999) have recently developed a more robust numerical simulation model of surface irrigation systems that includes an integrated optimization capability for the automated identification of appropriate design and management parameters. However, not all methods of identifying appropriate management practices require the use of simulation models. For example, Grismer and Tod (1994) developed a field procedure to calculate the optimal irrigation time for cracking clay soils using a simple field worksheet and volume balance calculation. The effect of specific management strategies on surface irrigation performance is discussed below.

3.3.2.1 Inflow rates

One of the most effective methods of varying the performance of surface irrigation systems is to alter the inflow rate of water application (Alazba and Fangmeier, 1995). However, as changes in the infiltration characteristics are difficult to predict, flexibility should be incorporated into the design and management of surface irrigation systems so that the system operation can be adjusted to maintain a high level of performance. Unfortunately, due to the labour requirements traditionally associated with surface irrigation management and a lack of automation within this sector, the majority of surface irrigation is currently conducted using a constant inflow rate.

Real-time control of irrigation implies the use of parameters measured during an irrigation to control that irrigation's management practice to produce a desired outcome. Opportunities exist to vary management during irrigation by altering the inflow rate (i.e. cutback) or by controlling the number or period of surges applied (Latimer and Reddell, 1989). A variety of simple techniques for varying inflow with automated controllers are already being used commercially (primarily "cut-back" and "cablegation" systems).

Cut-back irrigation normally involves reducing the rate of inflow by about half after the advance water has reached the end of the field. Cablegation is a semiautomatic system where the inflow rate is gradually reduced during the irrigation (James 1988). Alazba and Fangmeier (1995) found that inflow hydrograph shapes with the most flexibility produced the highest application efficiencies. However, while highly variable inflow hydrographs are conceptually possible, the creation of these hydrographs under commercial field conditions is not yet viable.

3.3.3.2 Agronomic practices

Cultivation has been found to more than double the infiltration under surface irrigation (Raine *et al.,* 1996). Cultivation before irrigation and mulching (wheat straw, oaten-hay or sown-oats) has also been found to significantly increase infiltration rate and wetted perimeter (Miller and Aarstard, 1971) increasing soil-water movement into the cropped beds (Sinclair *et al.* 1992). Seasonal variation in infiltration has been attributed to a reduction in the rate of initial infiltration rather than a decrease in the basal rate, which often remains relatively constant throughout the year (Izuno *et al.*, 1985; Wallender and Rayez, 1985). The hydraulic conductivity of surface seals have been found to be 1-8% of the conductivity of the underlying soil and result in an average 46% decrease in the infiltration within irrigated furrows (Segeren and Trout, 1989). This suggests that decreases in infiltration rate between the first and later irrigations in the season are most likely attributable to the formation of the surface seal.

Crop residues in irrigation furrows increase the resistance to surface flow, increasing depth of flow, opportunity time and infiltration, decrease irrigation uniformity and reduce soil erosion caused by flowing water (Evans *et al.* 1987; Raine and Bakker, 1996b). Water advance in grain crops on a sandy loam soil have also been found to be more than 70% greater in no-till furrows compared to clean-till furrows (Christensen *et al.*, 1994). While the effect on infiltration of cultivation and mulching generally decreases with subsequent irrigations, infiltration in straw and hay mulch treatments has been found to increase on the second irrigation due to anchoring of the mulch and then decrease with subsequent irrigations as the mulch decomposes (Sinclair *et al.*, 1992).

Furrow compaction has been successfully used to reduce infiltration on high infiltration soils and improve distribution uniformity (Raine *et al.*, 1996). On loamy sand soils, furrow compaction had a marked effect on infiltration, with the more compacted furrows exhibiting lower infiltration rates (Elliott *et al.* 1983; Raine and Bakker, 1996b). Wheel traffic has also been found to decrease advance times by a factor of 1.98 during the initial irrigation but have no affect on the advance times of subsequent irrigations (Christensen *et al.*, 1994).

The mean and variability of infiltration has been found to be greater for pre-planted than post-plant irrigations and soil variability in intake opportunity time (Childs et al. 1993). Similarly, the mean and variability of infiltration for structurally unstable sodic soils has been found to be smaller than for stable alluvial soils (Raine *et al.*, 1998). This suggests that where surface seals are the infiltration-limiting factor, the variability in infiltration rates is lower. Similarly, the variability in infiltration has been found to be lower between wheeled furrows than between non-wheeled furrows on a krasnozem soil (Smith *et al.* 1992).

The initial soil moisture content is an important determinant of infiltration in cracking clay soils (Maheshwari and Jayawardane, 1992) in that the majority of the infiltration when the soil is dry occurs through the crack volume. Hence, infiltration and deep drainage losses in these soils can be significantly reduced by the adoption of shorter irrigation schedules, which reduce the crack volume. Other advantages of more frequent scheduling on these soils include the faster irrigation advance and shorter irrigation periods.

3.3.3.3 Alternate furrow or wide-spaced furrow irrigation

Alternate furrow irrigation (AFI), skip row irrigation is the technique whereby water is applied to every second furrow rather than to every furrow. This practice is similar to wide-spaced furrow irrigation where the wider inter-furrow space is simply left as a single bed. The benefits of AFI are thought to be primarily related to a reduction in the loss of evaporation from the soil surface and a reduction in deep drainage losses. Griffin *et al.* (1966) has found that approximately 50% of the total evapotranspiration prior to canopy closure in sorghum crops is due to evaporation from the soil surface. However, following canopy closure the soil surface evaporation decreased to less than 10% of the total evapotranspiration.

Alternate furrow irrigation has been widely used (Box *et al.*, 1963: Stone *et al.*, 1979; Fishbach and Mulliner, 1974; Tsegaye *et al.*, 1993; Mitchell *et al.*, 1995; Bakker *et al.*, 1997) to reduce water use by up to 50% without loss of yield in potatoes, onions, wheat, corn, sorghum, cotton, peppermint and sugarcane. Increases in the productivity per unit of irrigation water applied have been widely observed (Talsma *et al.*, 1977; Musick and Dusek, 1982; Tsegaye *et al.*, 1993) suggesting that AFI is an appropriate technique in water limited environments. However, reductions in yield per unit area using AFI have been observed by several workers (Stone *et al.*, 1979; Stone *et al.*, 1982; Samadi and Sepaskah, 1984: Crabtree *et al.*, 1985; Bakker *et al.*, 1997) even though the production per unit water increased. In the case of Stone *et al.* (1979), sorghum yields were only decreased during seasons where the daily average rainfall was less than 1.6 mm and the daily wind movement >155 km. This suggests that the yield decrease was associated with inappropriate scheduling of the wide-spaced furrow treatments and is consistent with the results of Stone *et al.* (1982) who suggested that AFI should be abandoned during high water stress periods. Bakker *et al.* (1997) also found that scheduling the irrigations using a reduced water deficit was necessary to maintain sugarcane yields using AFI. However, it should also be noted that even though yield was reduced under these conditions using AFI, significant savings in the volume of water used and substantial reductions in the labour required to carry out irrigations (Stone and Nofziger, 1993; Mitchell *et al.*, 1995) were also achieved which, depending on the price of the water and labour, may have resulted in an improved crop profitability.

Torres *et al.* (1996) investigated the potential of AFI for sugarcane production over a seven-year period. An initial experiment conducted on a disturbed Vertosol soil found that AFI yielded 38 t/ha cane less than conventional every furrow irrigation (EFI). However, AFI was found to be much more successful on other soil types with water savings of 43-50% achieved under the Columbian conditions. The effect of alternating the actual furrow wetted using AFI was also investigated with no difference in yield found between this treatment and the traditional alternate furrow irrigation where the same furrows are wet on each irrigation. However, it should be noted that the number of irrigations conducted varied from two to five throughout the season with the cane yields ranging from 70 to 150 t/ha.

Stone *et al.* (1979) suggests that AFI would not work well on sandy soils and is best suited on medium to fine clay textured soils where substantial lateral movement is observed. Alternate furrow irrigation usually requires a longer period of irrigations due to slower water advance rates. However, this is dependent on the soil infiltration characteristic and the amount of lateral soil-water movement. Hodges *et al.* (1989) found that the rate of water advance where every furrow (spacing 1.42 m) was irrigated in a grain sorghum crop was 1.2 to 1.48 times faster than in wide-spaced furrows (spacing 2.48 m). However, advance rates of the wide-spaced treatments were no more variable than for the every-furrow irrigations. Lateral movement is often minimal in low infiltration soils and irrigation frequency will need to be increased to counter the reduced soil-moisture storage. Substantial lateral movement in cracking clay soils has been found (Torres *et al.*, 1996; Bakker *et al.*, 1997) resulting in advance times of AFI treatments which are almost twice as long as every furrow irrigations, with no subsequent improvement in the application efficiency. This suggests that AFI is inappropriate on these soils as a technique to reduce water application volumes.

3.3.3.4 Surge irrigation

Surge irrigation is the intermittent application of water to furrows or bays in a series of surges (or pulses) of constant or variable time span (Smith *et al.* 1992). The key reason for improved irrigation performance under surge irrigation is the decrease in the infiltration rate following the first surge (Coolridge *et al.* 1982; Podmore and Duke, 1982). However, the degree of infiltration reduction under surge irrigation is variable and difficult to predict. The use of surged applications also reduces the variability in advance times between successive irrigations and between furrows with different degrees of compaction (Izuno *et al.*, 1985). Mechanisms by which surge irrigation reduces infiltration include (Kemper *et al.* 1988):

- consolidation on the furrow perimeter due to increased soil water tension during flow interruption;
- filling of cracks which developed during flow interruption with bedload during the following surge;
- forced settlement of suspended sediment on the furrow perimeter when the water supply is interrupted; and
- greater sediment detachment and movement caused by more rapid advance of the surge stream front.

The intermittent wetting associated with surge irrigation has also been found to increase air entrapment and increase soil consolidation during the off-periods (Seymour and Podmore, 1989). Cycle ratio-time functions have been used to evaluate the differences in performance on opposite sides of T-type surge values producing uneven off-times and expanding cycle times (Cahoon and Eisenhauer, 1994).

Surge infiltration functions undergo a step reduction from the time dependent rate to the basic rate after one complete wetting and dewatering cycle (Izuno *et al.*, 1985). This infiltration rate reduction leads to a reduced time and water necessary to complete advance when surged applications are used instead of continuous applications. The use of surge irrigation in furrows with high levels of crop residue has been found to increase uniformity and reduce drainage losses (Evans *et al.* 1987). However, soils that reach steady state infiltration quickly are less likely to exhibit decreased infiltration rates as a result of surged flow (Cahoon and Eisenhauer, 1994). Similarly, while the magnitude of the infiltration rate change is greatest on relatively light textured soils (Testezlaf *et al.*, 1987), some clay soils exhibit little or no response to surging (Bautista and Wallender, 1985; Manges *et al.*, 1985; Pitts and Ferguson, 1985). For example, the use of surge irrigation has been found to have no significant effect on infiltration into Queensland cracking clay soil (Smith *et al.*, 1992). This is consistent with the view that infiltration on cracking clay soils is dominated by water entry via crack flows (Gardener, 1985) and that the final infiltration rate is reached relatively quickly irrespective of surging.

4. Defining a Uniform Approach to Whole Farm Irrigation Efficiency

The term *"efficiency"* is defined as the *"ratio of useful work done to the total energy expended"* (Turner, 1987). This ratio can be expressed as a percentage and applied to other inputs within any system including water in an irrigation context. Hence, a 100% efficient system (which only exists in an ideal world) is able to convert all of its inputs to output. A major aim in managing any real world system (e.g. a machine, or irrigation system) is to maximise its efficiency by minimising the outputs that escape as system losses or inefficiencies. Hence *"whole farm water use efficiency"* is the ratio of output from the water (or input) that is managed at the whole farm scale. A large number of other performance indicators or "indices" have also been proposed under the banner of water use efficiency. These can also be applied to whole farm water use efficiency. The Irrigation Association of Australia (IAA) has recently suggested that a uniform system of whole farm irrigation efficiency definition and measurement would allow meaningful comparison of water use within the various sectors of the irrigation industry (IAA, 1998).
Similarly, the Land and Water Resources Research and Development Corporation (LWRRDC) recently commissioned Barrett, Purcell and Associates (BPA, 1999) to consult with the Australian irrigation industry on the potential to adopt a consistent framework including terms and definitions for irrigation water use efficiency. As summarised in these reports water use efficiency has historically been defined in three main areas:

- Economic water use efficiency
- Agronomic water use efficiency
- Volumetric water use efficiency

4.1 Economic Water Use Efficiency

The aim is to achieve the highest farm gate value for the water being used. While the current price of water does not necessarily motivate high economic efficiencies, the corresponding value of production from that water should. High economic water use efficiency is not principally due to efficient irrigation water management but may be influenced by world markets etc. As it relates to irrigation, it might include: irrigating the higher value crops within your system/rotations; the cost/benefit of irrigation development; irrigation vs rainfed (dryland production); irrigation systems – e.g. surface vs spray vs drip; the cost of water; the cost of pumping and re-pumping water; irrigating larger areas (if not land limited); water budget on smaller ML/ha (higher risk water use); and greater reliability on rainfall.

$$\text{Gross Production Economic Water Use Index} = \frac{\$}{\text{Total Water Applied (ML)}}$$

$$\text{Irrigation Economic Water Use Index} = \frac{\$}{\text{Total Irrigation Applied (ML)}}$$

$$\text{Marginal Irrigation Economic Water Use Index} = \frac{\$\ \text{due to Irrigation}}{\text{Irrigation Water Applied (ML)}}$$

$$\text{Crop Economic Water Use Index} = \frac{\$}{\text{Evapotranspiration (mm)}}$$

The term "index" has been preferred in these definitions since the input and output have different dimensional units and therefore are not totally dependant variables (e.g. $ and ML). Conversely, the term "efficiency" is classically defined as a percentage or ratio of input to output of the same kind (e.g. ML/ML)

4.2 Agronomic Water Use Efficiency

The aim is to maximise the amount of useful (saleable) product for the unit of water used in the system. Again this value is not necessarily principally determined by efficient irrigation water management but may be influenced by crop nutrition, pest management and climate. This might include maximising yield and crop response to water by improved irrigation scheduling.

$$\text{Gross Production Water Use Index} = \frac{\text{Total Product (kg)}}{\text{Total Water Applied (ML)}}$$

$$\text{Irrigation Water Use Index} = \frac{\text{Total Product (kg)}}{\text{Irrigation Water Applied (ML)}}$$

$$\text{Marginal Irrigation Water Use Index} = \frac{\text{Marginal Production due to Irrigation (kg)}}{\text{Irrigation Water Applied (ML)}}$$

$$\text{Crop Water Use Index} = \frac{\text{Production (kg)}}{\text{Evapotranspiration (mm)}}$$

4.3 Volumetric Water Use Efficiency (ML used per ML diverted or %)

Efficiency

The volumetric approach to water use efficiency aims at maximising the volume of whole farm water that is of direct benefit to the crop. Conversely the aim is to reduce the volume of water that is lost in the whole farm system. This measure is perhaps the best measure of the whole farm level of performance and efficiency of water and irrigation management. This area of whole farm water use efficiency shall form the main part of this paper and has been used by the author in the bulk of the work performed over the last two years in the cotton industry.

The following water management sub-systems exist on most irrigated farms:
Supply systems (e.g. harvesting or lifting from river and captured overland flows; pumping groundwater from bores; and/or supply from irrigation scheme dams, channels and/or pipes);

- On-farm storage systems (e.g. ring tank storage cells; buffer holding dams; or catchment dams);
- On-farm distribution systems (e.g. earthen channels; gated pipes; or pressurised enclosed systems);
- Application systems (e.g. surface, spray, micro-systems); and
- Recycling systems (e.g. tail drains and tail water recycling channels and utilising supply harvesting pumps; or catch drains feeding into holding dams).

The efficiency of water use can be defined for each of these sub-systems based on the volumetric water inputs and outputs, or uses and losses. Potential volumetric losses (or inefficiencies) within each of the sub-systems must be measured or estimated accurately to quantify whole farm water use efficiency. Volumetric measurements of the water flows into and out of each unit are required and include, supply to and from the unit, rainfall, seepage (or percolation), evaporation, stored soil moisture, overland flows and tailwater recycling. In a purely volumetric sense, the efficiency of the system should be determined as the ratio of the water used by the plant to the water input. However, both the input and output water volume can be defined at a range of locations and over a range of time scales within the overall irrigation system.

The most commonly adopted definitions of irrigation water use efficiency are shown in Table 9 (BPA, 1999). It should be noted that the performance of scheme level water storage systems is commonly included in the conveyance efficiency term while the performance of on-farm storage systems is included in the distribution efficiency term.

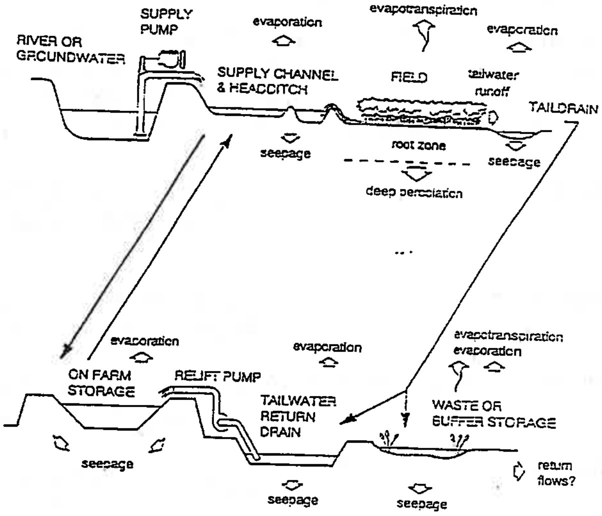

Figure 1: Whole farm irrigation flow and water balance

Table 9: Recommended Irrigation Efficiency Definitions for Australia
(from Barrett Purcell and Associates, 1999)

Term	*Definition*
Overall Project Efficiency (E_p)	*Irrigation water available to crop* / *Total inflow into system supply*
Conveyance Efficiency (E_c)	*Total outflow from system supply* / *Total inflow into system supply*
Distribution Efficiency (E_d)	*Water received at field inlets* / *Total outflow from system supply*
Field Application Efficiency (E_a)	*Irrigation water available to the crop* / *Water received at the field inlet*

The definitions proposed by BPA (1999) provide for a "nested" approach to a particular irrigation event (assuming no rainfall or unregulated flow into the supply system) where the overall project (or whole farm) efficiency can be calculated as:

$$E_p = E_c . E_d . E_a$$

A major concern with the sole use of volumetric efficiency terms for irrigation evaluation is that they do not provide any assessment of the overall irrigation performance in relation to crop production and economic returns. Hence in the assessment of the commercial viability or performance of an irrigation enterprise the economic and agronomic performance may also be used.

Irrigation Uniformity

An important component of the evaluation of in-field irrigation performance is the assessment of irrigation uniformity. As Burt (1998) points out, if a volume of water applied to a field is known only as the average applied over the whole field, then one half of the field has received less than the average applied and one half more than the average applied. Hence, if the average volume applied is the target application required to meet the crop requirements, one half of the field has been over-irrigated, reducing the efficiency of application, while the other half of the field has been under-irrigated, reducing yield. Thus, a major aim of irrigation management should be to apply water with a high degree of uniformity while keeping wastage to a minimum.

A wide range of irrigation uniformity coefficients are commonly used in performance evaluation (Jensen 1983). The Distribution Uniformity has also been used to assess the uniformity of surface irrigations (Merriam and Keller, 1978; Walker and Skogerboe, 1987). For surface irrigations, it is defined as the average infiltrated depth of water in the lower one-quarter of the field divided by the average infiltrated depth over the whole field. However, it should be noted that the larger the average applied length, the more likely *DU* will be large due to redistribution effects (Walker and Skogerboe, 1987). Another index that has been used (Walker, 1993) is the Absolute Distribution Uniformity (*ADU*) which is calculated by dividing the minimum depth applied to the field by the average depth applied to the entire field.

5. Methodology for On-farm Benchmarking and Validation

5.1 Development of On-farm Monitoring Equipment

As part of the whole farm performance benchmarking objective of this project it was necessary to develop accurate instrumentation to be used to measure those water inputs and outputs in the whole farm irrigation system in the efficiency definitions described above. As detailed above there are a vast array of whole farm irrigation water system inputs and outputs. To benchmark the performance of whole farm systems, individual farm water management units (i.e. storage, distribution and application) were assessed. Instrumentation included "off the shelf" sensors and data loggers and some equipment developed by the staff at the NCEA.

5.1.1 Farm water storages

To effectively monitor volume balances and water storage efficiencies in a large ring tank structure a system of accurate water level sensing along with a specific depth vs volume relationship for each storage was proposed. Water level, evaporation, rainfall and the ambient weather conditions were directly measured and logged at 15-minute interval continuously with modified weather station and water level and evaporation pan sensors. The combination of accurate water level and a depth volume relationship specific to that storage gave a continuous record of water inputs and outputs.

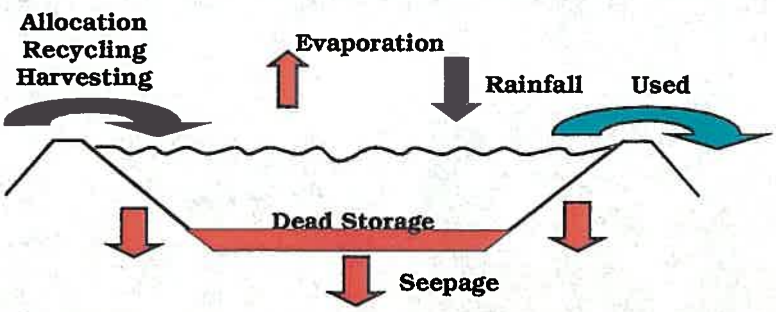

Figure 2: Water Storage and Distribution Channel Volume Balance

Figure 3: Storage monitoring equipment including weather station and logger (far left on bank); floating evaporation pan (middle) and shaft encoder water level instrument (near right)

When the system was behaving in a dynamic mode (i.e. either inflow or outflow occurring at high rates) seepage could not be separated out of the volume balance. This was the case through most of the irrigation season. However during non-pumping periods (typically in the off season) when the storage was in a static mode seepage was separated from the volume balance as the other rainfall and evaporation inputs and outputs were monitored. Table 10 and Figures 3 and 4 describe the water storage volume balance and efficiency monitoring equipment.

Table 10: On Farm water storage efficiency monitoring equipment

Efficiency Determination	Parameter	Method
On Farm Water Storage Efficiency and Volume Balance Monitoring	Storage Levels/Volumes	Shaft Encoder water level instrument
	Evaporation	Evaporation Pans and Weather station
	Seepage	Volume Balance
	Inflow	Water Level Sensor / Doppler meter
	Outflow	Water Level Sensor / Doppler meter
	Rainfall	Rain gauge
	Ambient weather parameters	Weather Station

Figure 4: Weather Station and logged rainfall and evaporation pan sensors monitoring conditions at storage

5.1.2 Distribution channels

A system of monitoring inflows and outflows in a distribution channel was proposed such that the difference between inflow and outflow would be equivalent to the system loss in that section of channel. To separate out evaporation and seepage, local evaporation pan data was used. To minimise flow monitoring inaccuracies in channels due to changing cross sectional area the flow meters were mounted (where possible) in fixed cross section pipes or culverts.

Channel depths were also monitored continuously over the season in three locations over each farm. Locations typically included main supply; head ditch and tailwater return channels. This data was used to estimate the channel seepage and evaporation losses during periods when these channels were in a static mode of no inflows or outflows, and purely subject to only seepage and evaporation losses.

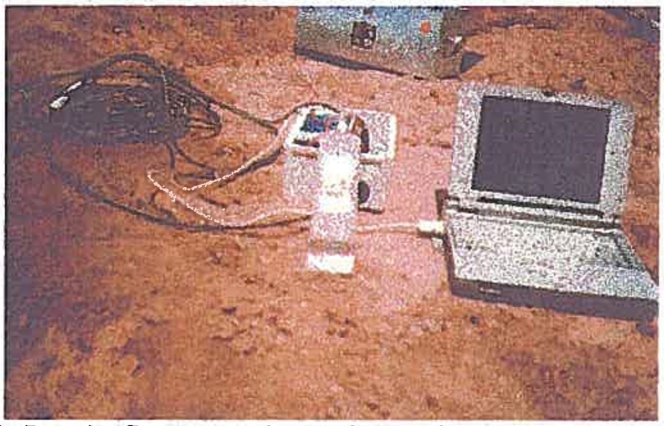

Figure 5: Ultrasonic Doppler flow meter, logger box and communications cable back to a laptop for downloading of data

Table 11: Distribution channel volume balance and efficiency monitoring equipment

Efficiency Determination	Parameter	Method
Distribution channels	Inflow Outflow Evaporation Seepage	Doppler flow meter Doppler flow meter Evaporation pan Channel depth sensors and Volume Balance

5.1.3 In-field application systems

Two approaches to determining the application efficiency of irrigation at a furrow scale were used. These were a direct in-field monitoring system (as in the storage and distribution volume balances) and a modelling system (SIRMOD surface irrigation model) which relies on well-proven theory and some simple furrow scale measurements.

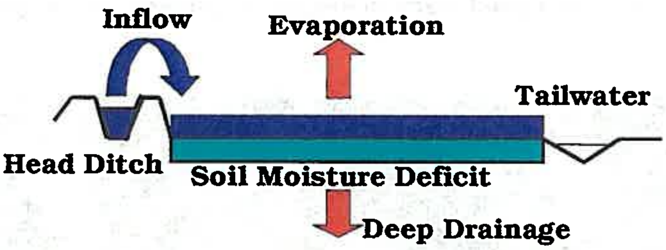

Figure 6: Field / Furrow Scale Volume Balance

The monitoring system involved the acquisition of furrow inflow and tailwater data logged continuously over each irrigation period and an assessment of the pre-irrigation soil moisture deficit using a Neutron probe or "Gopher" capacitance probe. A review of methods for directly measuring deep percolation over the season revealed that this would also be a complicated and costly exercise. Hence, in keeping with the simple measurement methods and minimal cost required, deep percolation and evaporation during furrow irrigation application were not attempted to be measured but rather formed the remainder of the volume balance as a combined loss component. This level of monitoring coupled with the modelling program gave sufficient data for both performance benchmarking and identification of the factors influencing in-field losses and inefficiencies.

Table 12: Furrow scale application volume balance and efficiency monitoring equipment

Efficiency Determination	Parameter	Method
Measured Parameters	Inflow Tailwater runoff Soil moisture deficit Deep drainage Evaporation	GLI tee mount meters in siphon GLI tee mount meters in tailwater pipe Neutron & Capacitance probe Loss term in volume balance (partitioning between losses not achievable through direct measurement)
Modelling Parameters	Advance Application flowrate Furrow slope Furrow shape Furrow length Required irrigation Modelling Tool	Logged switches / stopwatches GLI tee mount meters Survey Profile meter Survey Neutron & Capacitance probe SIRMOD surface irrigation model

Figure 7: GLI tee-mount meter in irrigation siphons measuring water applied

Figure 8: GLI tee-mount meter measuring tailwater from a furrow

5.2 Experimental Farm Site Selection

On-farm irrigation efficiency benchmarking and investigation of best management practices were undertaken over the 1998-2000 cotton seasons. In accordance with a CRDC directive, all farms monitored were located within the Border Rivers catchment. The farms and individual field sites monitored were chosen to represent the typical (a) soil types, (b) system design parameters (including storage depth, channel lengths and field lengths), and (c) operational management variables (including water storage operation, siphon size, irrigation strategy), found in the region. The relevant site specific characteristics are outlined in section 6.

Benchmarking of whole farm irrigation efficiency was undertaken during the first two seasons. The performance of the storage, distribution and application systems were measured on four farms (Farms A to D) during the 1998-99 season and on another four farms (Farms E to G) during the 1999-2000 season (Table 13). Alternative irrigation management practices were evaluated under on-farm during the 2000-01 season on Farm E.

Table 13: List of field sites and soil types

Farm	Soil Type
Farm A	Brown and grey cracking clays
Farm B	Black cracking clays;
Farm C	Red lighter sodic duplex soils
Farm D	Grey and red sodic duplex with underlying clays
Farm E	Brown and grey cracking clays
Farm F	Black, brown and grey cracking clays
Farm G	Red lighter sodic duplex soils

6. Whole Farm Irrigation Efficiency and Benchmarking Results

6.1 Whole Farm Irrigation Efficiency

The best and worst case whole farm water balances measured during the field trials are presented in Figure 9. The proportion of the whole farm water which was used by the crop in an individual irrigation event ranged from 21-65% (or 28-68% assuming complete recycling). Significant sources of volumetric water loss in both cases included storage evaporation (14% and 39%) and infield deep drainage (11 & 13%).

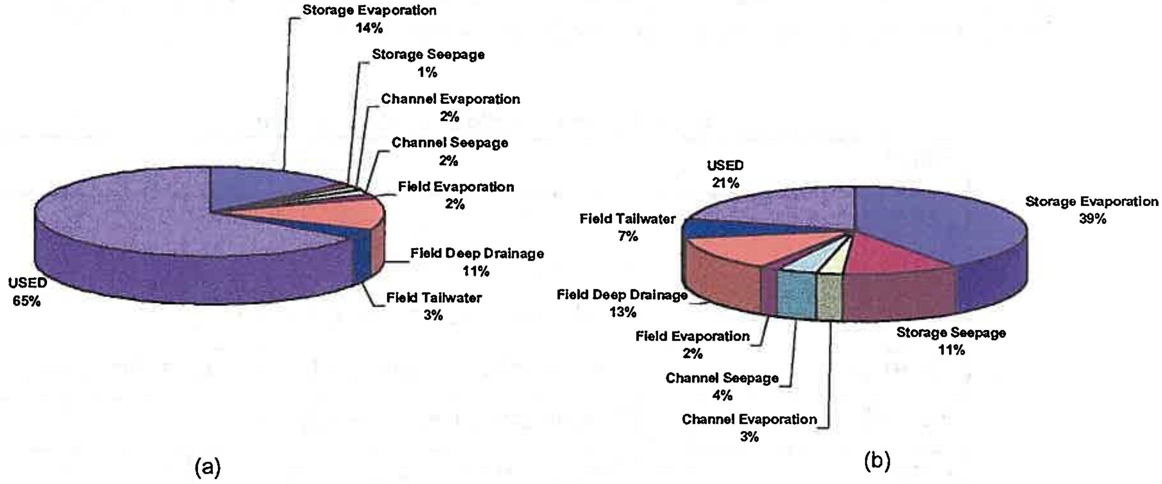

Figure 9 Components of the volume balance for (a) best and (b) worst case measured whole farm efficiencies

A summary of the best and worst case scenarios for the measured performance of the storage, distribution, and in-field application system components is shown in Figures 10-12. In each case, the efficiency is reported as a percent of the water volume entering each component of the system. Storage system performance ranged from 50-85% with evaporation ranging from 14-39% and seepage from 1-11% of the water stored. Distribution system efficiency was found to range from 87 to 96% with seepage representing between 2 and 8% of the distributed volume. The efficiency of the infield surface irrigation application ranged from 38-84% with tailwater volumes representing an additional 4 and 32% of the inflow water in these particular cases. Deep drainage in these cases ranged from 10 to 26% of the applied volume while surface evaporation represented only 2-4%. A more detailed outline of the efficiency results and the factors influencing the performance for each of the on-farm water management components is provided below.

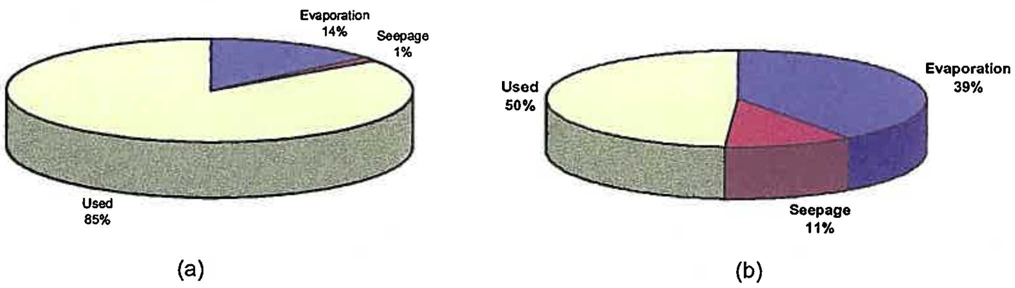

Figure 10 Components of the volume balance for (a) best and (b) worst case measured storage efficiencies

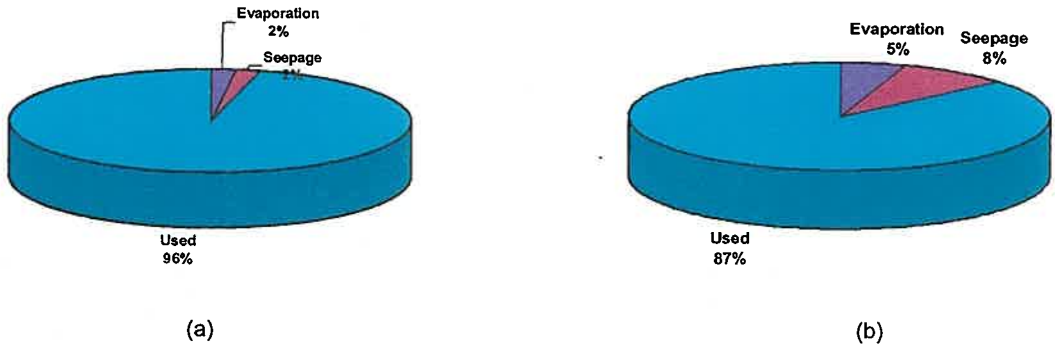

Figure 11 Components of the volume balance for (a) best and (b) worst case measured distribution efficiencies

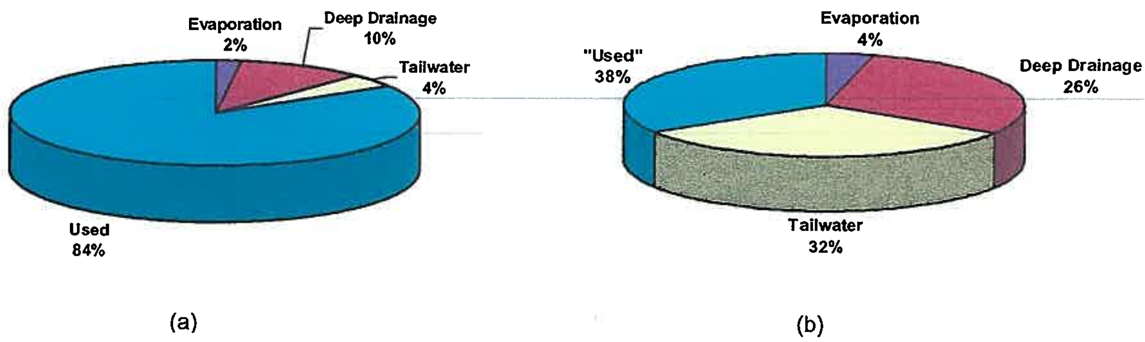

Figure 12 Components of the volume balance for (a) best and (b) worst case measured application efficiencies

6.2 Water Storage Efficiency

The results of storage efficiency measurements on four storages during the 1998/99 and 1999/00 seasons are presented below. The efficiencies are principally determined by the period of storage (and therefore opportunity time for evaporation and seepage) and the surface area to volume ratio of the total volume stored.

Table 14: Storage volume balance, efficiency and losses by volume (ML) and (percentage)

Storage Description	Storage Period	Stored Water	Used	Seepage	Evaporation	Storage Efficiency
Farm A 4m max depth 1800 ML	27/11/98 to 28/12/98	1272	1082 (85%)	14 (1.1%)	177 (13.9%)	85%
Farm A 4m max depth 2500 ML	27/11/98 to 5/7/99	2388	1203 (50.4%)	255 (10.7%)	930 (38.9%)	50%
Farm B 3m max depth 500ML	2/12/98 to 5/5/99	729	581 (79.7%)	34 (4.7%)	121 (16.6%)	80%
Farm E 4m max depth 1800ML	13/8/99 to 16/2/2000	3649	2776 (76.1%)	180 (4.9%)	701 (19.2%)	76%

For example, the first storage listed had a high storage efficiency (85%) since it was effectively emptied in one month. Similarly, the third and fourth storages listed were emptied and filled several times during the storage period such that the ratio of water used to water stored was high. Conversely, the second storage listed had a poor efficiency (50%) since it operated in a static mode for a long period allowing a significant percentage to be lost as evaporation.

6.3 Distribution Channels

Of the two methods for estimating channel losses the depth sensors provided for best means for estimating these losses. Table 15 shows the data for six channel depth monitoring systems during the season. While the use of channel depth and evaporation monitoring may be considered crude it does provide an estimate for the seepage of an integrated length of channel.

Seepage rates ranged from 1 to 23 mm/day. There is little evidence to explain the order of magnitude difference between the seepage values at the main supply channel and the tailwater channel at Farm A. One possible reason may be the interception of a prior stream with the distribution channel giving a localised region of high seepage in the channel. No further investigation was undertaken of this channel however it is suggested that after investigations similar to these show a potential high seepage rate in a channel that a more detailed investigation of the channel could be undertaken to find these localised seepage zones

Table 15: Distribution channel depth monitoring and resultant seepage estimations

Site	Average Daily Loss for period (mm/day)	Average Daily Evaporation for period (mm/day)	Resultant Seepage (mm/day)
Farm A main supply channel	14.6	13.6	1.0
Farm A TW channel	34	10.8	23.0
Farm B TW channel	31.2	12	19.2
Farm E head ditch	13.0	8.4	4.6
Farm E head ditch	11.9	8.4	3.5
Farm E TW channel	18.2	9.3	8.9

Using the higher value of seepage at farm A and the seasonal evaporation figures from the weather station, a conservative estimate of combined losses over 10km of main supply channel, 5km of tailwater return channel and 6km of head ditches can be made. For the opportunity time relating to seven irrigations (depending on whether it is main supply, tailwater return or head ditch) and measured channel width the losses were 270ML seepage and 130ML evaporation. In this case approximately 5000ML of water is distributed through the system for the season, which equates to an 8.6% distribution loss (6% seepage and 2.6% evaporation) through the system. Hence this equates to a whole farm water distribution efficiency of 91.4%.

Similarly using the only measured value of seepage for Farm B and seasonal evaporation figures a conservative estimate of combined losses over 12 km of combined main supply/head ditches and 10 km of tailwater return channel would be 109 ML seepage (or 8.4% of 1300 ML total farm water distributed) and 68 ML evaporation (or 5.2 % of total farm water distributed). Hence this equates to a 86.4% distribution efficiency.

Table16: Estimated channel losses on three farms based on seepage rates, evaporation rates, channel lengths and period of operation

Site	Distributed (ML)	Evaporation ML (%)	Seepage ML (%)	Distribution Efficiency (%)
Farm A	5000	130 (3%)	270 (6%)	**91 %**
Farm B	1300	68 (5%)	109 (8.4%)	**86 %**
Farm E	4800	94 (2%)	90 (1.8%)	**96 %**

6.4 Field Application Systems

A total of seventy individual irrigation events were monitored over two seasons on seven farms and eleven fields. Individual irrigation application efficiencies ranged from 37 to 100%. Average seasonal field efficiencies range from 70 to 90% (assuming full tailwater recycling). Tailwater runoff ranged from 4 to 32% and deep drainage from 11 – 30% (Table 17).

Seasonally, the total irrigation applied to these fields was in the range of 685mm to 940mm (average approx. 750mm or 7.5 ML/ha) with tailwater in the range of 27mm to 247mm and deep drainage in the range of 75mm to 235mm. Table 17 summarises the data in terms of individual and seasonal irrigation application efficiency, water balance and losses.

Table17: Summary of efficiency measurements on all fields during the project

Farm/Field	Individual Efficiency Range	Seasonal Efficiency	Seasonal Tailwater	Seasonal Deep Drainage
A	46 – 99%	86%	13%	14%
B	46 – 80%	71%	4%	29%
C	73 – 86%			
D/1	42%			
D/2	77%			
E/1	61 – 100%	90%	20%	10%
E/2	55 – 100%	84%	14%	16%
E/3	64 – 91%	81%	19%	19%
F/1	62 – 100%	89%	26%	11%
F/2	53 – 55%			
G	37 – 100%	70%	32%	30%

The following application efficiency and volume balance data tables (Table 18-29) report in more detail the results collected over the 1998/1999 season at farms A, B, C and D and over the 1999/2000 season at farms E, F and G. These tables give an indication of the amount of water applied during each irrigation, the length of irrigation and subsequent runoff volumes. Along with infiltration losses and the soil moisture deficit (calculated from pre and post irrigation neutron probe soil moisture readings), the efficiency of the irrigations has been determined considering both tailwater recycling and no tailwater recycling.

The water balance terms are expressed in depth dimensions (mm), which is effectively a volume per area (e.g. 1 ML/ha = 100mm). The term "I" denotes the irrigation applied in terms of its rate, time and total volume (expressed as a depth in mm), "TW" similarly denotes tailwater, "Deficit" is the pre-irrigation soil moisture deficit to full point, "DD" denotes deep drainage and "Evap" denotes an estimate of surface evaporation during the irrigation.

Application efficiency, "E_a"(as defined earlier) is expressed assuming both full tailwater recycling and no tailwater recycling. The term "DU" denotes the distribution uniformity of the irrigation application as defined earlier in this report and ER denotes the Requirement Efficiency which is defines whether the full requirement (or soil moisture deficit) is met (note in cases where application efficiency was 100% that this was due to the requirement not being fully met). Finally the term f_o denotes the steady state final infiltration rate of the soil in millimetres per hour and gives an indication of the potential for deep drainage losses during irrigation.

6.4.1 Application rates

The results show that in the main efficiencies are higher where application rates are higher. The main driver would be the minimisation of opportunity time for deep drainage to occur due to the fact that the water reaches the end of the furrow more quickly and is therefore shut off more quickly.

Many factors drive the siphon application rate. As an example,Table 24 Irrigation 7 shows that the measured flowrate between the four siphons side-by-side were differed by 18% (i.e. 7.1 vs 5.8 l/s). This is due to the simple placement of the siphon either up the outside of the head ditch (outlet control) or in the ponded rotobuk (inlet control). A further example is highlighted in Table 18, Irrigations seven and eight where siphon application rates were measured at both ends of the head ditch with a 25% variation in application from the low head to the high head end of the head ditch (e.g. 1.52l/s vs 2.34l/s). It should be emphasized that there is an upper limit in application rates determined by furrow erosion, furrow overtopping and ensuring that under-irrigation does not occur.

6.4.2 Application times

The application time (as determined by the siphon cut-off time) is a major factor in determining irrigation efficiency and the subsequent opportunity time for increased volumes of tailwater and deep drainage. Table 21 shows that in Irrigation nine tailwater ran for some 922 minutes of the total 1140 minutes of irrigation. This resulted in 355mm being applied to a 30mm deficit such that tailwater equaled 120mm and deep drainage 206mm for a single irrigation event. While this is an extreme case of poor management other less extreme cases also demonstrate that higher efficiencies are achievable through better management of application time.

As an example Table 24 shows in Irrigation 7 a trial of different cut off times. The treatments were as follows:

- Control – normal practice
- Treatment 1 – pull siphon when water at end of furrow
- Treatment 2 – pull siphon when water was 50m from end of furrow
- Treatment 3 – pull siphon 100m from end

Treatment 1 and treatment 2 can be directly compared as the same inflow time but at different flowrate. The main impact is the reduced requirement efficiency showing that the furrow was under-watered in both cases but significantly in the case of the lower flow rate.

Given that the control and treatments 1 and 3 were at similar flowrates then the effect of different siphon cut-off times can be directly compared. Treatment 3 demonstrates the effect of pulling the siphons when the water advance front was 100m from the end of the furrow. In this case tailwater was reduced by 9.5mm for the irrigation application. Consequently the application efficiency was higher and no sacrifice in the distribution uniformity or requirement efficiency was incurred. Further to this an application saving of 8mm was saved through pulling the siphons earlier. Hence the equivalent of 17.5mm (or 0.175 ML/ha) less water was required to be pumped as either supply to the field or tailwater). If this was extrapolated for the whole season (i.e. 8 irrigations) then a total pumping saving of 1.4 ML/ha could be achieved. At an average cost of $1/ML/m head (at an average farm lift of 8m) then approx. $10 per ha of pumping costs could be saved. Other savings that were not quantified could include: reduction in tailwater and storage siltation; reduced water-logging over the whole field (in particular the end of the field due to better drainage of tailwater)

6.4.3 Matching applied irrigation with deficit

The basic outcome of poorer application efficiencies could be phrased another way. That is that irrigation applied does not match irrigation required. The common belief in the industry is that the soils self-regulate the volume being applied. As an example, Table 18 shows that for Irrigation six, 100mm was applied to meet a deficit of 40mm. While deficits are usually measured through commercial Neutron Probe (and other soil moisture monitoring) services little thought is given to matching the volume of water applied to the deficit. Since volume applied is a function of application rate and application time then it is suggested that achievement of higher efficiencies could be gained simply through a better knowledge of these variables on an irrigation event basis. Hence a more detailed irrigation monitoring system is recommended to achieve this along with a strategy to then match applied and required irrigation volumes.

6.4.4 Early and late season irrigations

There is an obvious difference in the application efficiency in early and later season irrigations. Certainly the first or pre-water irrigations are significantly less efficient, which is most likely due to the more permeable nature of the soil at this stage.

Table 18: Application efficiency and volume balance data for Farm A

Irrigation No. and Date	I (l/s)	I (min)	I (mm)	TW (l/s/)	TW (min)	TW (mm)	Deficit (mm)	DD+Evap + error (mm)	TW %	DD+E +error (%)	Ea (no TW loss) %	Ea (full TW loss) %
3	1.25	719	72.3				35.5					49.1
10/12/98	1.25	719	89.8	0.2567	130	21.7	35.5	32.6	24.2	36.3	63.7	39.5
4 21/12/98	1.34	1216	130.0				50.2					38.6
6	1.55	685	84.9	1.45	336	39.1	39.9	6.0	46.0	7.0	93	47.0
7/1/99	1.94	650	100.9	0.5705	143	6.6	39.9	54.5	6.5	54.0	46.0	39.5
	1.94	650	100.9	0.9038	330	23.9	39.9	37.2	23.6	36.8	63.2	39.5
7	1.58	818	103.6	1.303	176	18.4	84	1.2	17.8	1.2	98.8	81.1
17/1/99	2.01	540	86.7	0.6287	129	6.5	78	2.2	7.5	2.5	97.5	90.0
8	1.52	973	118.6	1.0583	91	7.8	99.3	11.6	6.6	9.7	90.3	83.7
15/2/99	1.52	973	118.6	0.3907	175	5.5	99.3	13.8	4.6	11.6	88.4	83.7
	2.34	648	105	0.9884	269	8.5	89	7.5	8.1	7.2	92.8	84.8
16/2/99												
Total			**750mm ***			**100mm #**	**545mm @**	**105mm**	**13%**	**14%**	**86%**	**73%**

(* Assumes averages between measured applications when more than one is recorded and that initial two unmeasured irrigations were 70mm and irrigation 5 was 100mm)
(# Assumes tailwaters of 10mm per irrigation on irrigations that were not recorded)
(@ Assumes deficits of 50 mm in irrigations 1,2 and 5)
(! Assumes infiltration of 80mm in irrigations 1,2,4 and 5)

Table 19: Application efficiency and volume balance data for Farm B

Irrigation No. and Date	I (l/s)	I (min)	I (mm)	TW (l/s/)	TW (min)	TW (mm)	Deficit (mm)	DD+Evap + error (mm)	TW %	DD+E +error (%)	Ea (no TW loss) %	Ea (full TW loss) %
1 16/10/98	1.53	632	96.58				50					51.7
2	1.94	550	106.7	1.27	54	6.97	42.8	56.9	6.5	53.4	46.6	40.1
09/12/98	1.35	474	64.41	1.27	54	6.97	42.8	14.6	10.8	22.7	77.3	66.4
3 23/12/98	2.34	549	128.64	0.78	98	7.77	71.32	49.6	6.0	38.5	61.5	55.4
4 07/01/99	2.16	345	74.67	0.43	13	0.35	54.11		0.5	27.1	72.9	72.5
5 19/01/99	2.25	495	111.85				85.39					76.3
7 11/02/99	1.88	359	67.68	0.28	35	0.99	53.11	13.6	1.5	20.1	79.6	78.5
8 22/02/99	2.16	556	120.42	0.28	49	1.41	86.93	32.1	1.2	26.6	73.4	72.2
Total			**685**			**27 #**	**443**	**197**	**4%**	**29%**	**71%**	**67%**

(# Assumes average tailwater per irrigation on irrigations that were not recorded)
(@ Assumes infiltration of 80mm in irrigation 1 and 100mm on irrigation 5)

Table 20: Application efficiency and volume balance data for Farm C

Irrigation No. and Date	I (l/s)	I (min)	I (mm)	TW (l/s/)	TW (min)	TW (mm)	Deficit (mm)	DD+Evap +error (mm)	TW %	DD+E +error (%)	Ea (no TW loss) %	Ea (full TW loss) %
1 **15/10/98**	2.68	556	61.5	0.145		5.2	40	16.3	8.4	26.6	73.4	65.0
2 **04/12/98**	0.59 0.85	1104 1489	49.49 95.26	0.2 0.2	155 155	2.38	40 40	7.1	4.8	14.4	85.6	80.8
6 **16/02/99**	1.69	1188	150.56	0.39	328	9.69	100	40.9	6.4	27.1	72.9	66.4

(Note: soil moisture deficits were not measured at this site and hence deficits are estimated at 40mm early in the season and 100 mm later in the season)
(Estimates of totals for the season are not attempted since not all irrigations were measured)

Table 21: Application efficiency and volume balance data for Field 1, Farm D

Irrigation No. and Date	I (l/s)	I (min)	I (mm)	TW (l/s/)	TW (min)	TW (mm)	Deficit (mm)	DD+Evap + error (mm)	TW %	DD+E +error (%)	Ea (no TW loss) %	Ea (full TW loss) %
3 **23/12/98**	1.82	1967	430				85	345		80.2		19.8
9 **22/02/99**	2.59	1140	355	1.08	922	120	30	206	34	58	42	8.4

(Estimates of totals for the season are not attempted since not all irrigations were measured)

Table 22: Application efficiency and volume balance data for Field 2, Farm D

Irrigation No. and Date	I (l/s)	I (min)	I (mm)	TW (l/s/)	TW (min)	TW (mm)	Deficit (mm)	DD+Evap + error (mm)	TW %	DD+E +error (%)	Ea (no TW loss) %	Ea (full TW loss) %
2 **22/12/98**	1.15	2373	162.76	0.53 0.05	649 665	20.80 2.09	105	37	12.8	22.7	77.3	64.5
6 **08/02/99**	0.84	1137	57.37				48	9.4		16.3		83.7

(Estimates of totals for the season are not attempted since not all irrigations were measured)

Table 23: Application efficiency and volume balance data for Field 1, Farm E

Irrigation No. and Date	I (l/s)	I (min)	I (mm)	TW (l/s/)	TW (min)	TW (mm)	Deficit (mm)	DD+Evap +error (mm)	TW %	DD+Evap +error (%)	Ea (no TW loss) %	Ea (full TW loss) %	DU %	Er (%)	fo (mm/hr)
1 1/10/99	4.00	1235	168	2.3	255	20	120	28	12	17	83	71	94	100	1.7
2 4/12/99							80								
3 26/12/99	3.9	918	121	1.6	180	10	64	47	8	39	61	53	87	100	3.2
4 11/01/00	3.8	518	66	2.0	325	23	64	0	34	0	100	66	100	50	0
5 20/01/00	4.00	397	54	0.4	160	2	56	0	4	0	100	96	99	93	0
6 31/01/00	3.5	838	100	2.5	475	40	65	0	40	0	100	60	100	92	0
7 08/01/00							67								
8 25/02/00	3.4	660	78	2.9	225	22	60	0	28	0	100	71	100	100	0
Total			782			156	576	75	20%	10%	90%	70%			

* No application or tailwater data for irrigation 2 and 7 – assume average inflow for seasonal totals

Table 24: Application efficiency and volume balance data for Field 2, Farm E

Irrigation No. and Date	I (l/s)	I (min)	I (mm)	TW (l/s/)	TW (min)	TW (mm)	Deficit (mm)	DD+E +error (mm)	TW %	DD+E +error (%)	Ea (no TW loss) %	Ea (full TW loss) %	DU %	Er (%)	fo (mm/hr)
1 – 01/10/99	5.1	889	116	4.1	260	21	80	16	17.8	13.6	86.4	68.6	94	100	1.7
2 – 04/12/99	5.6	740	108	3.2	195	16	54	38	15	35	65	50	95	100	1.6
	5.6	740	108	2.1	175	9	54	45	9	42	59	50	82	100	4.9
	5.9	740	113	2.9	170	13	54	47	11	41	59	48	90	100	3.0
	5.9	740	113	2.3	140	8	54	51	8	45	55	48	86	100	4.2
3 – 26/12/99	5.8	837	127	3.2	240	20	69	38	16	30	70	54	93	100	4.3
4 – 11/01/00	5.4	650	90	2.8	295	21	65	4	24	4	95	72	90	95	3.8
5 – 20/01/00	6.1	380	61	1.6	65	2.7	64	0	4	0	100	96	80	88	5.8
			61	0.6	75	1.2	64	0	2	0	100	98	71	73	8.4
			61	1.0	100	2.6	64	0	4	0	100	96	75	89	7.2
			61	1.7	150	6.4	64	0	11	0	100	89	83	84	5.8
6 – 31/01/00	4.0	816	84	2.4	355	22	85	0	26	0	100	74	97	74	0.6
7 – 08/02/00															
Control	6.9	463	83	1.34	200	15	80	0	18.3	0	100	82	91	85	
Treatment 1	6.9	442	79	1.06	130	10	80	0	12.6	0	100	88	93	86	
Treatment 2	5.8	441	66	1.26	110	8.5	80	0	13.0	0	100	87	92	72	
Treatment 3	7.1	413	75	0.76	100	5.5	80	0	7.4	0	100	93	98	88	
8 – 25/02/00	6.5	554	93	2.3	155	9.3	76	7	10	8	92	82	93	100	2.5
TOTAL			767			123	573	110	16%	14%	84%	70%			

Table 25: Application efficiency and volume balance data at Field 3, Farm E

Irrigation No. and Date	I (l/s)	I (min)	I (mm)	TW (l/s/)	TW (min)	TW (mm)	Deficit (mm)	DD+E error (mm)	TW %	DD+E error (%)	Ea (no TW loss) %	Ea (full TW loss) %	DU %	Er (%)	fo (mm/hr)
1 01/10/99	3.6	873	132	2.5	425	44	80	8	34	13	90	61	96	100	1.3
2 04/12/99 *			76			15	46	15							
3 26/12/99	3.2	703	93	1	50	2	57	34	2.4	36	64	62	77	100	3.9
4 11/01/00	3.5	600	87	1.3	150	8	59	20	9	23	77	68	85	10	4.2
5 20/01/00	3.3	425	58	1.4	165	9	44	5	16	8	91	75	89	99	3.4
6 31/01/00	4.00	546	91	2.2	175	16	67	8	17	9	91	74	100	95	2.0
7 08/02/00	3.2	695	92	1.9	265	21	60	11	22	12	88	65	100	94	1.6
8 24/02/00	3.3	773	106	2.1	300	26	53	27	25	26	74	49	100	96	1.3
Total			**735**			**141**	**466**	**128**	**19 %**	**19 %**	**81 %**	**62 %**			

* No application or tailwater data for irrigation 2 – assume average inflow for seasonal totals

Table 26: Application efficiency and volume balance data for Field 1, Farm F

Irrigation No. and Date	I (l/s)	I (min)	I (mm)	TW (l/s)	TW (min)	TW (mm)	Deficit (mm)	DD+E +error (mm)	TW %	DD+E +error (%)	Ea (no TW loss) %	Ea (full TW loss) %	DU %	Er (%)	fo (mm/hr)
1 01/10/99	2.42	799	177	1.3	340	41	100	36	23	20	74	56	92	100	3.8
2 10/12/99	2.25	959	198	1.7	565	74	114	10	37	5	92	58	95	100	3
3 02/01/00	5.62	491	128	3	180	25	64	39	20	30	62	50	90	100	7
4 17/01/00	5.14	450	107	2.9	110	11	80	16	10	15	83	75	87	100	6.2
5 29/01/00	5.57	484	123	4.9	230	35	84	4	28	3	91	68	97	100	1.7
6 09/02/00	5.3	500	122	5	295	36	131	0	30	0	100	71	99	66	0.8
7 26/02/00	4.52	404	85	3.4	210	24	73	0	28	0	100	72	93	51	3.1
Total			**940**			**246**	**646**	**105**	**26%**	**11%**	**89%**	**63%**			

Table 27: Application efficiency and volume balance data for Field 2, Farm F

Irrigation No. and Date	I (l/s)	I (min)	I (mm)	TW (l/s/)	TW (min)	TW (mm)	Deficit (mm)	DD+Evap +error (mm)	TW %	DD+Evap +error (%)	Ea (no TW loss) %	Ea (full TW loss) %	DU %	Er (%)	fo (mm/hr)
1 01/10/99							70.0								
2 10/12/99							68.5								
3 03/01/00	4.45	494	190	1.4	315	35	86	69	18	36	55	45	88	100	16
4 17/01/00	5.51	366	172	2.6	240	51	64	57	30	33	53	37	89	100	15
5 22/01/00							35.0						97	100	1.7
6 02/02/00							76.1						99	66	0.8
7 09/02/00	4.38	504	189.57				48.7						93	51	3.1
8 26/02/00							57.8								

(Estimates of totals for the season are not attempted since not all irrigations were measured)

Table 28: Application efficiency and volume balance data for Field 3, Farm F

Irrigation No. and Date	I (l/s)	I (min)	I (mm)	TW (l/s/)	TW (min)	TW (mm)	Deficit (mm)	DD+E +error (mm)	TW %	DD+E +error (%)	Ea (no TW loss) %	Ea (full TW loss) %	DU %	Er (%)	fo (mm/hr)
1 01/10/99							70.0								
2 10/12/99							52.8								
3 02/01/00	6.15	578	237.44				43.3						88	100	16
4 17/01/00	5.60	577	215.90				38.1						87	100	6.2
5 22/01/00							30.0						97	100	1.7
6 02/02/00							33.1						99	66	0.8
7 10/02/00	4.43	472	146.07				37.8						93	51	3.1
8 26/02/00	4.34	728	210.99				43.4								

(Estimates of totals for the season are not attempted since not all irrigations were measured)

Table 29: Application efficiency and volume balance data at Field 1, Farm G

Irrigation No. and Date	I (l/s)	I (min)	I (mm)	TW (l/s)	TW (min)	TW (mm)	Deficit (mm)	DD+E +error (mm)	TW %	DD+E +error (%)	Ea (no TW loss) %	Ea (full TW loss) %	DU %	Er (%)	fo (mm/hr)
1 29/09/99	0.83	1161	115	0.31	933	35	70.0	10	31	8	92	61	96	95	3.8
2 11/12/99	5.00	559	168	2.4	230	71	57.4	40	42	24	76	34	88	100	18
3 08/01/00	2.57	807	242	1.7	645	123	60.4	59	51	24	76	25	96	100	6.3
4 21/01/00															
Control	2.61	300	140	1.4	40	4	59.6	76	3	54	44	43	94	100	10.1
Treatment 1	7.92	223	227	3.7	144	67	59.6	100	30	44	37	26	90	100	25.7
Treatment 2	1.89	230	108	0.9	240	53.2	59.6	0	49	0	100	51	99	94	3.0
Treatment 3	3.79	231	214	1.8	150	66	59.6	88	31	41	40	28	93	100	19.5
5 01/02/00	4.5	200	113	1.7	65	14	49.4	50	12	44	50	44	90	100	14.3
TOTAL			778			247	297	235	32%	30%	70%	38%			

7. Assessment of Alternative Irrigation Practices

7.1 Preliminary Assessment of Management and Design Parameters

The major opportunities for improving whole farm water use efficiency were identified from the field data as:

- water storage evaporation mitigation; and
- reduction of in-field deep drainage and tailwater losses through improved management of irrigation application.

7.1.1 Water storage evaporation mitigation

Some 14-39% of stored water measured on the trial farms was lost due to evaporation. Evaporation mitigation could be achieved through several methods including:

- deepening storages to reduce the surface area to volume ratio of the storage
- using multiple cells to reduce the surface area of free water available to evaporation
- tree shelter belts to reduce the wind speed and thus the evaporation over storages
- storage surface coverings

As an example a cost benefit analysis for building deeper storages is presented in Table 30. The main comparison is a 5m square ring tank and a 7.5m square ring (while a comparison with round construction is also presented). The costs associated with deeper storages include greater earthworks associated with stronger embankments and longer haul distances. Savings (or benefits) include significant water and area savings. The comparison between a 5m and a 7.5m square construction shows that 22% of water is saved from evaporation losses while the earthworks cost is two and a half times greater. However given the stated gross margin figure for cotton the benefits in extra production due to the water savings are such that the extra construction costs are recouped in two years.

Table 30: Cost benefit of deepening water storages to reduce evaporation volume and percentage - Water Storage Design Comparisons for a 3500ML storage at Goondiwindi

Wall Height (m)	**5**	**7.5**	**7.5**	**10**
Water depth (m)	4.2	8.7	8.7	12.4
Shape	Square	Square	Round	Round
Area (hectares)	76	42	44	28
Earthworks (m^3)	349,600	654,887	592,876	888,483
Earthworks unit cost ($\$/m^3$)	1.00	1.33	1.3	1.25
Earthworks cost ($)	$349,600	$871,000	$770,739	$1,110,604
Av. Evaporation on Yearly basis (m)	1.8			
ML lost to Evap.	1521	734	736	516
% Evap Loss	43%	21%	21%	15%
Extra ha of crop production (@ 6ML/ha)	0	131	131	167
Extra $ (@ $1976/ha gross margin)	0	$258,856	$258,856	$329,992
Years to pay back extra investment	**-**	**2.01**	**1.62**	**2.3**

Mitigation of storage evaporation remains the "Holy Grail" of improving whole farm water use efficiency. Practices such as building deeper storages, multiple cells and wind shelters serve only to reduce the evaporation by a certain percentage (often difficult to predict the benefit to undertake a cost benefit analysis). Perhaps the only solution that could completely mitigate evaporation would be to cover the storage.

Cost, value of the water conserved, construction, life of the product and pay back period all need to be considered in the cost benefit equation. To date, the cost of such a scheme has been largely prohibitive. Practical limitations have also been difficult to overcome. Assuming one hundred per cent evaporation reduction Table 31 shows the cost recovery equation for investing in evaporation mitigation covers. As an example, if water was valued at $300 per megalitre (opportunity cost) then a water storage evaporation mitigation cover costing $2.25 per m^2 would be paid back in 5 years.

Table 31: Maximum cost of evaporation cover material based on water value and payback period (not amortised)

Value of water per Megalitre	$300	$400	$500	$600
Payback period (yrs)	*Maximum cost of storage cover material per square metre*			
1	$0.45	$0.60	$0.75	$0.9
2	$0.90	$1.20	$1.50	$1.80
5	$2.25	$3.00	$3.75	$4.50
10	$4.50	$6.00	$7.50	$9.00

(Note: if considering higher payback periods the guaranteed life span must be considered)

While these two evaporation reduction techniques demonstrate various degrees of evaporation reduction any evaporation mitigation should take a systems approach and consider what is the best alternative in terms of the climate, whole farm irrigation management, storage management, water resource availability and the cost of mitigation. Any potential evaporation mitigation strategy may include a combination of mitigation options.

7.1.2 Improved management of irrigation application

Application rates and cut-off times

A significant loss of water at the whole farm level is deep drainage associated with the in-field application system (Figure 9). On the farms measured, deep drainage typically represented 1–2 ML/ha (or 11–30%) and tailwater volumes represented 0.3–2 ML/ha (or 4–32%) of the 6.8–9.4 ML/ha applied to the field. In the best and worst cases measured, deep drainage represented 11 & 13% of the whole farm water while 3-7% ended up as tailwater.

Some initial modelling work was undertaken using the SIRMOD surface irrigation simulation model to quantify the effect of managing irrigation application rates and cut-off times to reduce deep drainage and thus, increase application efficiency. The results of these simulations are presented in Tables 32 and 33. This data shows that in this case, the management of irrigation application rate and siphon pull time would significantly affect the irrigation efficiency. For most fields monitored, the optimum siphon pull time was identified when the water advance was still a substantial distance from the end of the furrow. Existing applications rates were also found to be far from optimal, and typically determined by low heads and excessively small siphon sizes.

Table 32: Effect of irrigation cut-off time on Application Efficiency (E_a) and Distribution Uniformity (DU) of a mid-season irrigation, field length of 1000m, slope 1:2500, and deficit of 70 mm

Cut off time (hr:min)	Cut off distance from end (m)	Applied (mm)	Infiltrated (mm)	Tailwater (mm)	Deep Drainage (mm)	E_a (no TW recyc.)	E_a (90% TW recyc.)	DU (%)
8:00	past end	144	108	36.1	38	48.6	62.8	94
7:20	past end	132	104.5	27.5	34.5	53.0	65.3	93
6:40	50	120	100.5	19.5	30.5	58.3	68.3	92
6:00	120	108	96.5	11.5	26.5	64.8	71.7	90

Table 33: Effect of pulling siphons early and increasing the application rate by 1.5 times on a 1000m furrow with 3" siphons and a 50mm irrigation requirement

Siphon pull / application rate	Application Efficiency (%)	Applied Volume (mm)	Tailwater (mm)	Deep Drainage (mm)
actual - after 90mins of tailwater	57	88	8.5	29.5
when water reaches the end	65	77	3	24
and with 1.5 x app rate	71	70	5.3	15
when water is at 25m from the end	69	72	0	22
and with 1.5 x app rate	73	68.5	4.2	14.3
when water is at 50m from the end*	70	71	0	21
and with 1.5 x app rate	75	66.7	3.1	13.6
when water is at 100m from the end*	72	65	0	15
and with 1.5 x app rate	80	62.3	0.5	11.8

* Note in these two cases the end was marginally under-irrigated

Table 32 shows that when siphons were shut off even when the water was 120m (or 10% of the field length) from the end that the water effectively irrigated the end of the row and subsequently reduced tailwater from 36.1mm to 11.5mm and deep drainage from 38mm to 26mm. Table 33 shows that the combination of this with an increase in siphon application rate achieves a further efficiency gain.

Field length

Farm design parameters such as field length also have a strong relationship with the optimum application efficiency that can be achieved. In the case of this field it is inherently difficult to irrigate efficiently due to the length of 1000m and the low slope of 1 in 2500. Even with a high level of management of the application rate and cut-off time only approximately 75% efficiency can be achieved. However, Table 34 shows that higher efficiencies can be achieved with shorter field lengths. Trading off costs against the benefits of shorter field lengths, optimum field lengths of 600 to 700m would be advisable in this case. In other cases factors such application rate (determined by head and siphon size) and field slope should be considered.

Table 34: Optimising Application Efficiency (E_a) and Distribution Uniformity (DU) of a mid-season irrigation by modifying field length for a slope 1:2500 and soil moisture deficit of 70 mm, optimised siphon cut off times and application rate of 8 L/s

Field Length (m)	Application Rate (L/s/furrow)	Optimum cut off time (min)	Optimum cut off distance from end (m)	Ea – with 90% tailwater recycling (%)	DU (%)
600	8	200	110	91	86
700	8	240	130	86.9	84
800	8	280	140	83.8	84
900	8	360	140	75.9	85
1000	8	400	180	74.4	83

It should be noted that the data representing the effect of the improved irrigation application practices above was firstly tested using the SIRMOD surface irrigation simulation and design package. As a first step towards optimising irrigation application, the testing of different design and management strategies to improving irrigation application efficiency should be undertaken using the SIRMOD package. This approach is recommended for site-specific design rather than using generic conclusions from the data generated in Tables 32, 33 and 34

7.2 Field Evaluation of Modified Siphon Application Rate and Period of Application on Irrigation Efficiency

The objectives within the project to both develop efficiency monitoring systems and optimise irrigation efficiency through improved management were married through the development of the Irrimate™ package of irrigation efficiency monitoring and optimisation. The Irrimate surface irrigation evaluation package was trialled to identify optimum irrigation siphon application rates and period of irrigation on a comparative analysis for two similar fields in Goondiwindi. Both fields consisted of grey clay soils, had similar management history and have typically yielded similarly. Field 19 (conventional) was irrigated under conventional farm irrigation management. Field 20 (alternative management) was monitored using Irrimate and then recommendations were made to in terms of application rate and irrigation time to minimise deep drainage and tailwater and maximise irrigation application efficiency (see Table 35). Irrimate monitoring hardware includes the siphon flow meter placed in the siphon at the field head ditch and the furrow advance meter's placed at five locations, equally spaced along the furrow. Irrigation flow rate, advance times and period of irrigation were used in the SIRMOD simulation model to optimise the application rate and irrigation cut-off parameters.

Detailed measurements of irrigation and rainfall volume balance were also undertaken. Rainfall was measured using rain gauges on site. Bulk field inflows (ML applied) and outflows (ML tailwater/runoff) were measured using Starflow ultrasonic doppler water meters placed in the head ditch supply and tailwater outflow pipes. Soil moisture was monitored using Enviroscan capacitance probes and Hydroprobe neutron probes in parallel. Cotton yield was recorded from the cotton gin and using precision agriculture yield mapping technology.

Table 35: Comparison of conventional and Irrimate optimised fields

Field 19 (conventional)	Field 20 (Irrimate monitored and modified management)
Field length = 520m	Field length = 520m
Slope = 1:800	Slope = 1:800
alternate furrow irrigation (non-watering of wheel tracks)	alternate furrow irrigation (non-watering of wheel tracks)
one x 2 inch siphon per alternate furrow (approx. 1-6-2.2 l/s per furrow)	one x 2 inch & one x 2½ inch siphons per alternate furrow (approx. 4.5 – 5 l/s per furrow)
Irrigation shut off when water was well past end of furrow	Recommended that irrigation be shut off when water was 50 m from end of furrow*

(* While this was the recommendation it was not always adopted by the irrigator)

Detailed volumetric and agronomic irrigation efficiency performance indicators were measured for each field. This data is shown as a seasonal summary in Table 36. Perhaps the most obvious conclusion from the data is that there was significantly greater crop water use in the modified practice field, which was also reflected by a greater amount of water applied. However this greater crop water use did not return a higher crop yield. One possible reason for this is that both fields were managed agronomically the same. While the modified practice field may have been using more water (only realised upon viewing the data after the season had finished) and growing faster there was no regulation of growth (i.e. growth regulator application was the same for both fields). Physiologically, greater crop water use should produce greater vegetative growth. However the nature of the cotton plant is such that this may not produce extra cotton lint (i.e. reproductively) but rather yield more vegetatively. As this was only recognised in hindsight upon viewing the data, measurements of plant dry matter production (or internode lengths) were not taken.

Table 36: Summary of Irrigation Efficiency performance indicators.

Performance Indicator Value	Control Field	Modified Management Field
Total Irrigation Water Applied (mm)	775	967
Rainfall (mm)	405	405
Irrigation + Rainfall Applied (mm)	1180	1352
Total Irrigation Tailwater (mm)	198	192
Rainfall Runoff (mm)	90	71
Tailwater +Rainfall runoff (mm)	288	251
Effective rainfall (mm)	271	285
Irrigation Deep Drainage	84	116
Rainfall Deep Drainage	44	49
Total Deep Drainage	128	166
Total Crop Water use (mm)	764	935
Irrigation crop water use (mm)	494	659
Yield (bales/ha)	8.1	7.0
Water logging over last 5 irrigations	111 hrs (or 4.6 days)	70 hrs (or 2.9 days)
Agronomic WUE (bales/ML)	1.05	0.74
Volumetric Irrigation Efficiency (ML used/ML delivered or %) assumes 90% tailwater recycling	83%	84%

Efficiency of individual irrigation events

Individual irrigations were monitored in both fields. Irrigation applied, tailwater and soil moisture deficit were measured directly as well as advance measurements for SIRMOD simulations. The "deep drainage" term is derived via a volume balance method.

Table 37: Irrigation water balance and efficiency of conventional field

Irrig	Flow Rate (L/s)	Time (min)	Applied (mm)	Tailwater (mm)	Infiltrated (mm)	Deficit (mm)	Deep Drainage (mm)	Application Efficiency* (%)	Distribution Uniformity (%)
1	1.9	1690	189	54	135	111	24	79%	97%
2	1.8	860	89	15	74	72	2	96%	90%
3	1.5	1250	107	26	81	67	14	80%	95%
4	1.6	1070	95	23	72	68	4	91%	93%
5	2	755	88	13	75	56	19	73%	87%
6	2	875	101	30	71	61	10	82%	95%
7	2.6	705	106	37	68	59	9	82%	98%
TOTAL			775	198	578	494	84	83%	

Table 38: Irrigation water balance and efficiency of modified management field

Irrig	Flow Rate (l/s)	Time (min)	Applied (mm)	Tailwater (mm)	Infiltrated (mm)	Deficit (mm)	Deep Drainage (mm)	Application Efficiency* (%)	Distribution Uniformity (%)
1	5.1	680	197	50	147	134	13	88%	95%
2	5.1	594	177	33	144	98	46	67%	95%
3	5.1	445	131	27	104	81	23	76%	95%
4	4.7	450	120	28	92	79	13	83%	92%
5	4	285	84	10	74	72	2	96%	94%
6	5.5	470	142	25	117	100	17	84%	92%
7	4.8	425	116	19	97	95	2	96%	98%
TOTAL			967	192	775	659	116	84%	

(* Assumes 90% of tailwater is recycled and not lost in system)

The data shows that irrigation efficiency was only marginally higher in the modified field due mainly to higher crop water use. While optimal irrigation flowrate recommendations (using the IRRIMATE/SIRMOD tools) were made for the modified practice field, the irrigation manager did not adhere to the irrigation timing recommendations. One reason may be that fine tuning the period of irrigation to just meet the crop watering requirements was seen as too risky by the irrigator. Hence, the irrigator employed a large factor of safety by continuing to run excess water down furrows for some 1-2 hours after the water after the recommended period. As an example, irrigations 5 and 7 (Table 38) show the very high application efficiencies achieved for two irrigations where the siphon was stopped much closer to that recommended by the IRRIMATE/SIRMOD tools.

To further demonstrate the potential impact of pulling the siphons at the recommended time, Table 39 shows the volume balance and efficiency data from these irrigations as simulated using SIRMOD and the optimal siphon cut off time. Generally the data shown in Table 39 was achieved in the simulation by a siphon cut-off time matching the time when the water reached the end of the furrow. Compared with the conventional field, this equates to a significant saving in tailwater (172mm), a negligible deep drainage saving, less water delivered (6 mm) and far greater crop water use (165mm or 33% greater). The impact of the greater crop water use is discussed below.

Table 39: SIRMOD simulated irrigation water balance and efficiency of modified management field

Irrig	Flow Rate (l/s)	Time (min)	Applied (mm)	Tailwater (mm)	Infiltrated (mm)	Deficit (mm)	Deep Drainage (mm)	Application Efficiency* (%)	Distribution Uniformity (%)
1	5.1	480	140	3	137	134	3	98%	92%
2	5.1	510	145	5	140	98	42	70%	93%
3	5.1	340	100	2	98	81	17	82%	91%
4	4.7	320	86	1	85	79	6	93%	91%
5	4	285	84	10	74	72	2	96%	94%
6	5.5	370	115	2	113	100	13	88%	87%
7	4.8	360	99	3	96	95	1	99%	97%
TOTAL			769	26	743	659	84	89%	

(* assumes 90% of tailwater is recycled and not lost in system)

Crop water use

Perhaps the most obvious outcome from the trial was the fact that Field 20 (modified management) had a significantly higher crop water use yet had a lower yield. Figure 15 shows a comparison of daily water useages between the two fields. Daily water use was similar early in the season for the period of first and second irrigations. However for the latter part of the season daily water use was often higher in Field 20. Figure 14 demonstrates this further with the seasonal cumulative crop water use being greater for Field 20. In particular, the crop water usage rate increased after the second irrigation.

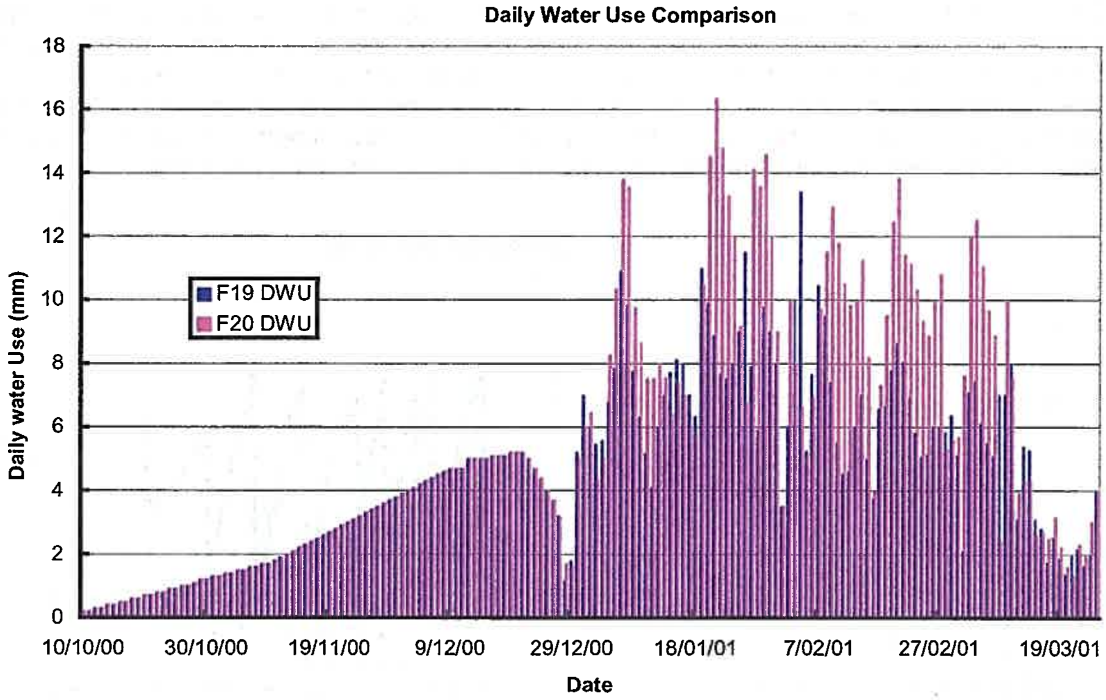

Figure 13: Daily crop water use comparisons between fields

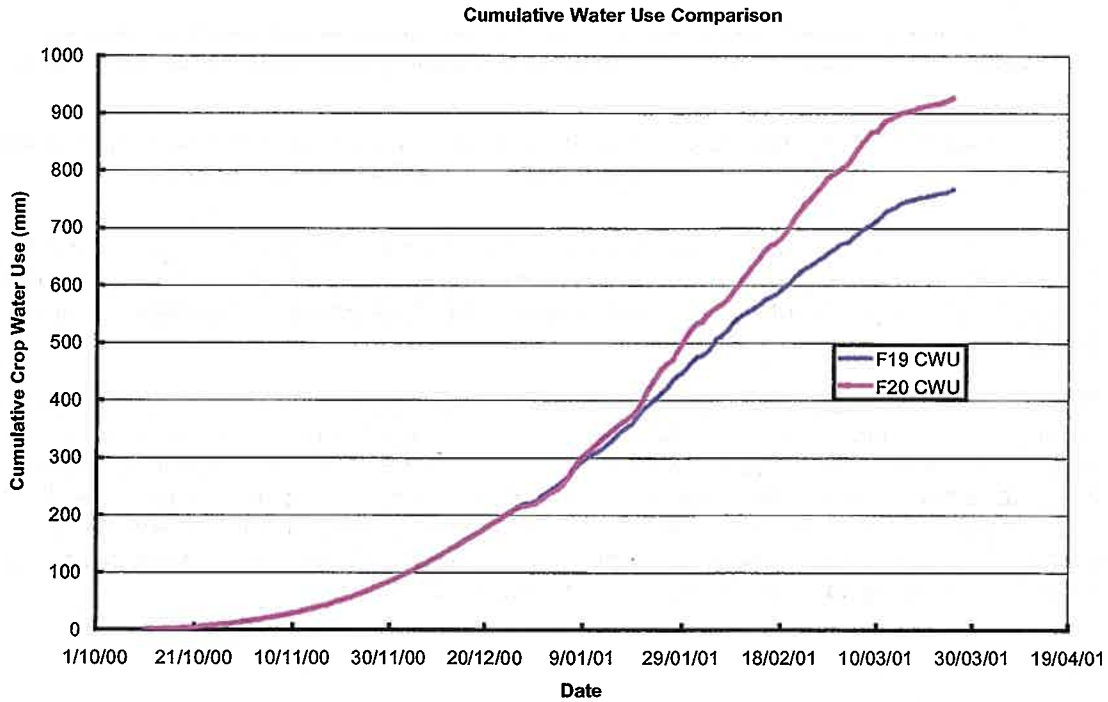

Figure 14: Cumulative crop water use comparisons between fields

Soil moisture responses

To demonstrate soil moisture relationships during the season, continuous soil moisture data is presented in Figure 15. The obvious features of this data include the greater upper and lower limit for Field 20, the result of which is an overall greater crop water use (as shown also in Figure 14). The higher upper limit was most likely due to the greater wetting up of the top 10 cm soil layer in the bed due to the greater furrow flowrate causing a greater furrow flow depth. This type of wetting up would increase bed wetting around the seed and therefore enhance germination. Hence running greater furrow flowrates and water depths during a "pre-water" or "water-up" (i.e. first irrigation) may be a good practice where germination is difficult.

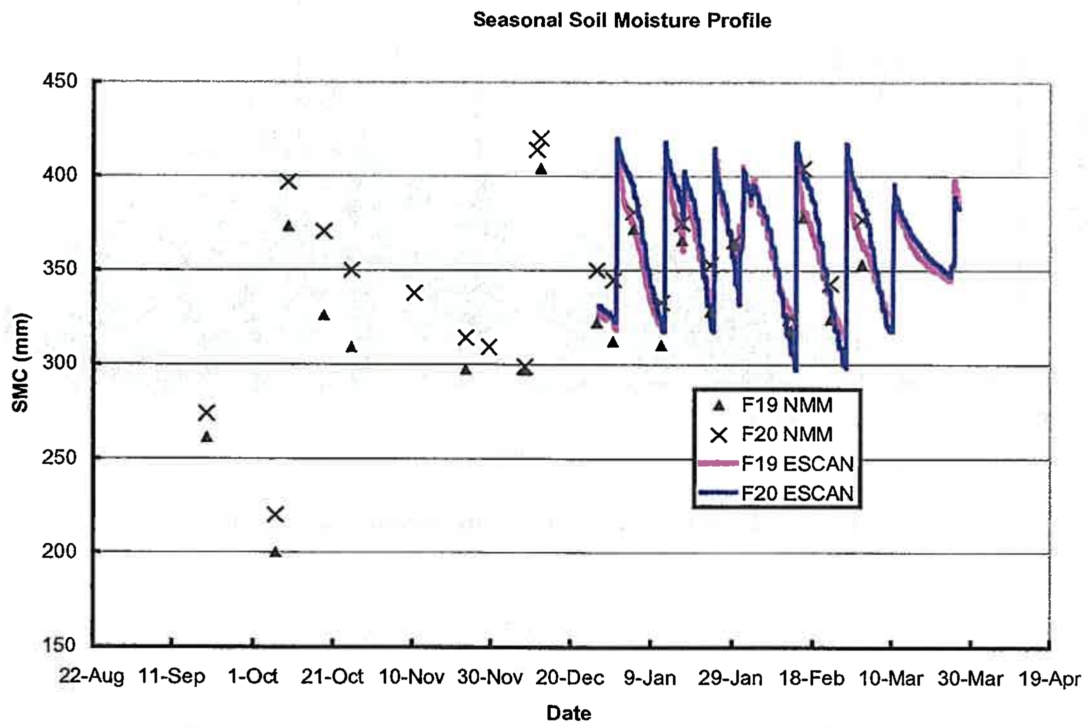

Figure 15: Soil moisture profile for the season including neutron probe readings and continuous enviroscan readings for the last five irrigations

Figure 16 shows the continuous soil moisture values for the individual soil layers within the root zone profile. These are shown for the last five irrigations only since continuous soil moisture readings were only taken for that period. The soil moisture profiles show distinct soil moisture relations.

The soil moisture levels are generally higher in the top layers in Field 20. This greater wetting up of the top 10 cm soil layer in the bed due to the greater furrow flowrate causing a greater furrow flow depth. This type of wetting up would increase bed wetting around the seed and therefore enhance germination. Hence running greater furrow flowrates and water depths during a "pre-water" or "water-up" (i.e. first irrigation) may be a good practice where germination is difficult The soil moisture profiles show reduced periods of low water usage typical of post saturation waterlogging stress for the modified practice field.

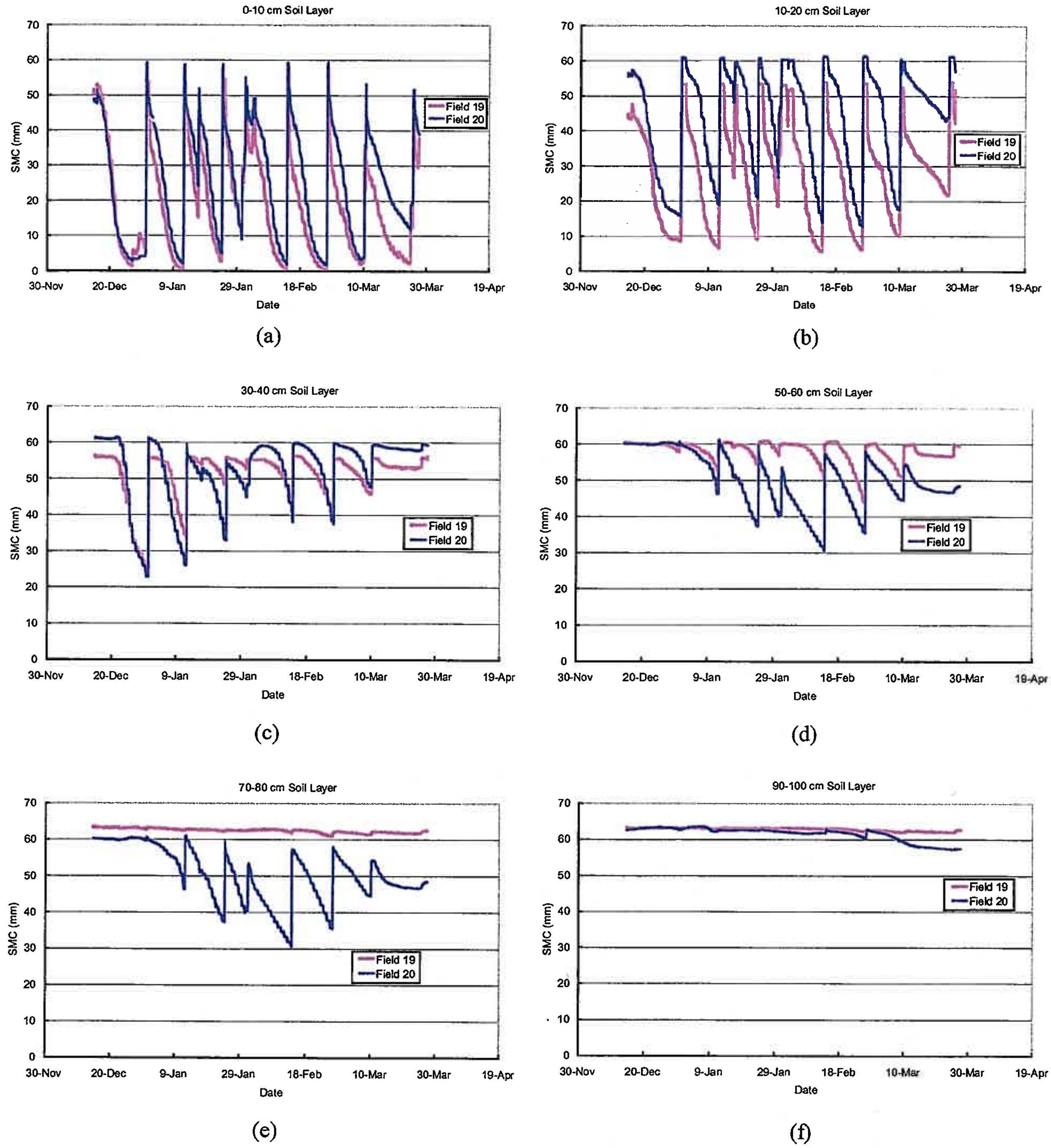

Figure 16: Soil layer moisture plots (a-f) for the last five irrigations

Soil moisture was extracted from the 70-80cm and 90-100cm depths by the crop in the modified practice field as indicated in Figures 16 e & f. The conventional field showed minimal soil moisture extraction from these depths.

Conclusions

The truest indicator of the success of any management change must be an improvement in profit and productivity. Given that irrigation efficiencies were similar between the two fields (although the modified practice field could have been optimised further by some 5% efficiency) conclusions must be drawn from the response of the crop. While limited agronomic data was collected some basic conclusions can be drawn, viz.:

- The modified practice field used significantly (33%) more water (Irrigation use was 659mm vs 494mm for the normal management field). Water extraction was similar at shallow depths but far greater at deeper levels in the modified practice field
- The crop yield was significantly less in the modified management field (7.0 bales/ha vs 8.1 bales/ha for the normal practice field)
- The conventional practice field matured some seven days earlier than the modified management field, which indicates a significant physiological difference between the two fields.
- Apart from yield the crop physiological effects were not well understood in this trial due to limited data
- Soil moisture data would suggest that the modified management field underwent less waterlogging stress as indicated by earlier crop water use recovery after irrigation events.

While the yield data would conclude against the management practices suggested by the Irrimate surface irrigation evaluation system there is distinct contradiction shown in the soil moisture data. This would suggest that the issues that are interacting are agronomic and physiological. Unfortunately these interactions were not measured or understood during the trial and hence further trials with more extensive agronomic and crop physiological monitoring may answer some questions to do with optimising yield in accordance with crop water use.

8. Discussion of Results Including Likely Impact of The Results for the Cotton Industry

8.1 Review of Previous Whole Farm Irrigation Research and the Identification of Opportunities for Improvement (Phase 1)

The reviewed literature and data shows that there is both considerable potential for improvement in irrigation efficiency of surface irrigated production systems as well as considerable opportunity to make this improvement through changes in management and farm design to reduce water losses on farm. Opportunities to improve whole farm WUE include:

- water storage seepage and evaporation mitigation;
- distribution channel seepage and evaporation mitigation;
- in-field application deep drainage and tailwater loss minimisation; and
- agronomic irrigation improvements including the reduction of water logging stress through the minimisation of irrigation inundation.

There is no doubt that the results and data from this project highlight that a real opportunity for irrigators in the Australian Cotton Industry exists in the area of improving water use efficiency for greater productivity. The main barrier to the adoption of water saving techniques and technologies will be the economic capital outlay required for such measures as evaporation mitigation and seepage control measures. The modification of in-field irrigation management practices that give demonstrable gains of irrigation efficiency is a simple and inexpensive way of making small efficiency gains

The improvement of agronomic WUE is a complex issue that needs further work. However the initial findings of this project demonstrate that reduction in irrigation saturation time has a significant potential to reduce waterlogging stress and improve crop water use efficiency.

8.2 Benchmarking Whole Farm Irrigation Efficiency (Phase 2)

The benchmarking of whole farm WUE showed that the farms monitored in the Goondiwindi region had the following ranges of water losses on a whole of farm water basis

- Storage Evaporation – 14-40%
- Storage Seepage – 1-10%
- Channel Evaporation – 2-3%
- Channel Seepage – 2-4%
- In-field deep drainage – 11-13%
- In-field evaporation – 2%
- In-field tailwater – 3-7%

These benchmark figures show that significant potential for irrigation efficiency improvements exists in the water storage and application systems. In these cases minimal losses were measured in distribution channels however this may not be generalised for the whole industry based on soil type variations.

This data demonstrates that there is significant scope for securing farm water through efficiency gains. The ability to improve whole farm efficiency is shown by the fact that in a worst case only 21% of the total farm water was utilised by the crop compared with a best case (benchmark) farm that utilised 70% of whole farm water through the crop. The challenge is how to economically secure this water through alternative design and management practices.

8.3 Best Management Practices - Assessment of Alternative Irrigation Management Practices to Improve Irrigation Efficiency (Phase 3)

8.3.1 Water storage evaporation reduction

The data from the benchmarking phase of this project demonstrates that some 10 to 40% of water is lost due to evaporation from water storages. Thus, evaporation represents the single largest preventable loss of water from on-farm irrigation storages in Australia. The problem is exacerbated by the nature of these on farm storages, which are relatively shallow (less than 5.0metres). The present volume of on-farm storage in the Condamine - Balonne, MacIntyre, Gwydir and Namoi Valleys now totals almost 1,000,000 ML.

The average annual evaporation rate in these areas can be over 1500mm giving a nett loss (evaporation in excess of rainfall) of up to 1000mm. This coupled with the relatively low storage depths leads to a potential loss through evaporation of up to 20% of stored volume or 200,000 ML per annum. The potential value of this water for cotton production alone is over $600 per megalitre. The total annual cost of evaporative losses in these regions may exceed $120million per annum. These economic imperatives are secondary to the ongoing search for more water to meet the increasing need to provide adequate environmental flows. Being able to control evaporation in a practical and economic fashion is a uniquely safe method of increasing the available water resource within the Murray Darling System.

The data presented in Tables 30 and 31 show the cost benefit of two different types of evaporation mitigation measures. While these are simulated examples there needs to be a proof on concept of these types of measures such as the viability of deepening storages and the practicalities of covering large on farm water storages. Other possible best management practices might include multiple storage cell to reduce surface area and evaporation and higher level design criteria for deeper dams including site selection to minimise seepage and failures.

8.3.2 Reducing in-field deep drainage and tailwater

The initial trial work in this project indicates that combinations of optimised application flow rate; irrigation time and field design parameters (such as field length) all have a significant effect on the volumetric efficiency of furrow irrigation applications. In very long fields (up to 1000m) with inappropriate siphon application rates and times water savings of the order of 0.5 ML/ha per season (or 10%) could be expected through deep drainage and tailwater savings. In such a case planting areas could be budgeted at 0.5ML/ha less giving 10% greater irrigated cotton area planted. The potential benefits for the Australian cotton industry could be in the order of $100 million extra cotton production. Further the savings in tailwater pumping costs at a cost of $1 per ML per metre head of water pumped could result in pumping savings in the order of $5.5 million. Of course the greater level of labour to manage irrigations to achieve optimum efficiencies would offset some of these savings and production benefits.

While the savings in water are well demonstrated in the project these alternative irrigation management practices within current agronomic monitoring schemes has produced a significant effect on crop yield. Further work is needed on the effect of reducing water logging and irrigation inundation times and the effect of various soil moisture deficits on the crop response and yield of the cotton plant. Paradigm shifts may be needed in terms of plant variety and crop monitoring systems to push agronomic and volumetric water use efficiency benchmarks to a higher level.

8.4 Extension (Phase 4)

The awareness raised in this project of the relative values and potential improvements in whole farm water use efficiency is not an insignificant component of the value built by the project but one that is difficult to quantify. Perhaps the value is best measured by the plethora of activity and new projects current within the cotton industry in the area of water use efficiency that was not existent when the project commenced in 1998. Examples of these include:

- water use efficiency initiatives are established in QLD and NSW to provide support to irrigators to improve water use efficiency;
- irrigators now are able to understand the opportunities that exist in water use efficiencies and potential savings in their farms; and
- irrigation efficiency evaluation is developing as a service that can be provided to irrigators.

9. Description of Project Technology

There is no doubt that without some means to be able to measure and quantify whole farm irrigation efficiency the assessment of farm irrigation performance is not achievable. Perhaps one of the main outcomes of the project was the development of the "Irrimate" technology which utilises the software developed for the furrow soil infiltration characterisation model (INFILT) at USQ and the SIRMOD simulation model. The Irrimate hardware was produced by the NCEA in association with this project to develop farmer friendly tools for irrigation performance evaluation. However, in reality these tools are not "farmer friendly" but rather "consultant friendly" since the feedback throughout the project indicated that farmers would prefer to pay a cotton or irrigation consultant to do this type of assessment.

The Irrimate package consists of irrigation monitoring hardware including siphon flow rate and total flow monitor (Fig 21) and irrigation advance sensors (Fig 22) placed along the length of the furrow. The advance sensors are used in conjunction with the Kostiakov-Lewis equation to quantify the infiltration characteristic of the soil within the furrow. The model (SIRMOD, developed by Utah State University and University of Southern Queensland) can be used in conjunction with the data gathered from the Irrimate hardware to simulate the irrigation. After accurate simulation is achieved (according to a volume balance match and irrigation advance time match between real and simulated) the model can be used to analyse post irrigation data to provide the most efficient regime of irrigation application rate and time.

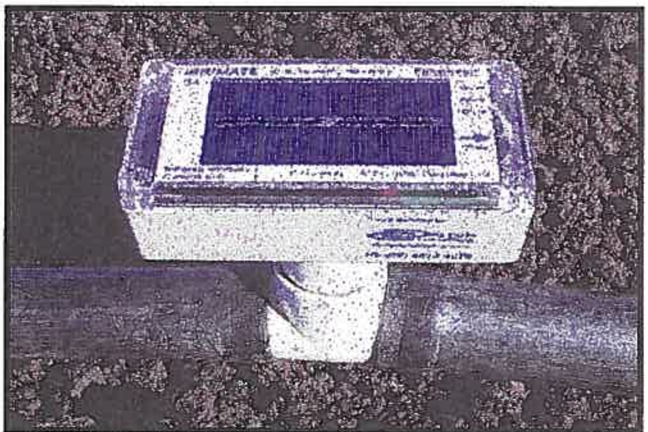

Figure 17: Irrimate siphon flow-monitoring hardware

Figure 18: Irrimate furrow advance monitoring hardware and download device

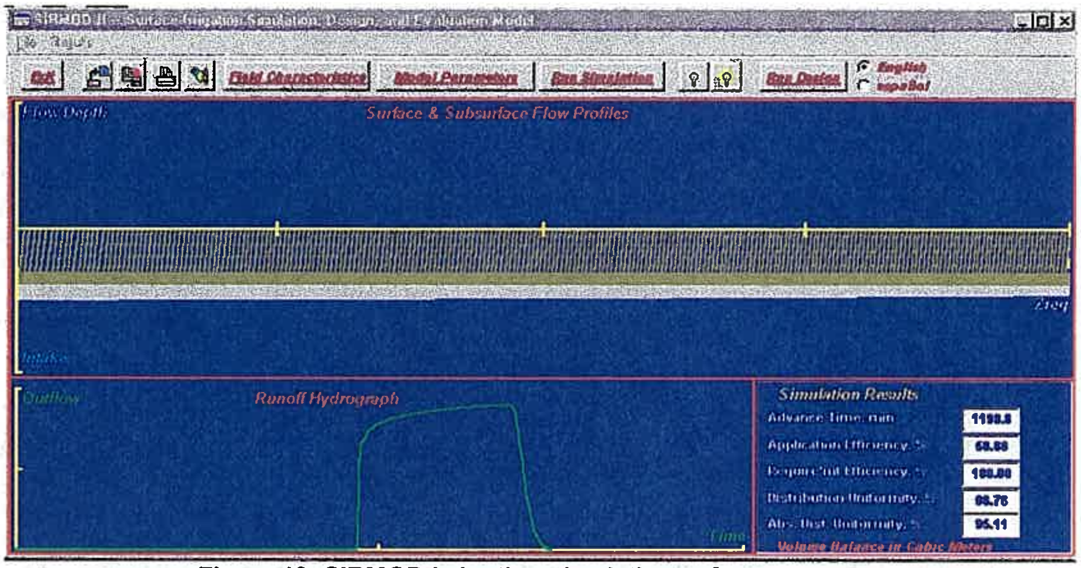

Figure 19: SIRMOD irrigation simulation software output

10. Further Development, Dissemination and Exploitation of the Project

The project team have invested heavily in developing and disseminating the tools, data and outcomes of the project. However, further scope to disseminate and exploit the project outcomes is possible in several areas.

Training and Extension Programs

"Measure it to manage it" workshops have been held in eight cotton growing valleys to create awareness of whole farm irrigation efficiency and promote irrigation best management practice. However, further workshops could be conducted either in other areas or as repeat workshops in those valleys where workshops have been conducted. Alternatively, follow-on workshops which provide a more detailed exposure to the advantages of comparative benchmarking and/or a greater level of grower confidence in using the decision support tools could be developed.

The NCEA has developed a suite of training modules for irrigation industry training of extension officers, irrigation designers and irrigation practitioners. Training in whole farm irrigation efficiency assessment has been undertaken by WUE IDO's employed through NSWAg and QDPI. As is generally the case, a basic knowledge and understanding of the issues influencing water use efficiency and its improvement will further develop the evolution of improved irrigation management and water use efficiency. Many modules have been developed by different training providers in irrigation. However, there is not yet an adequate module on the assessment and evaluation of the performance of surface irrigation systems. Further training of IDO's, cotton consultants and irrigators in this area would exploit the knowledge built in the project.

Some basic whole farm water use efficiency promotional and extension sheets have been developed by this project. However, there is a need to further develop the range of information resources readily available to cotton irrigators. The resources could take the form of information fact sheets, training courses, decision support systems and internet accessible materials.

Evaluation of Agronomic Impacts of Changed Surface Irrigation Management

Preliminary field evaluation of the potential benefits of reduced waterlogging associated with improved surface irrigation has been conducted. However, further research is required to confirm the range of conditions under which benefits could be expected and the management practices required to consistently achieve those benefits. This work should be conducted in such as way as to include the full range of soil, agronomic and climatic differences experienced within the industry.

Economic Assessment of Surface Irrigation Systems and Associated Infrastructure

This project has quantified the performance of the various on-farm water management systems. While preliminary economic assessments of some system and management changes have been conducted, more detailed studies are required to assist growers make decisions based on the cost/benefit of suggested infrastructure and management changes.

Evaporation of water from farm storages represents the largest farm water loss. Many of the options for surface evaporation mitigation have been reviewed in this project. However, the cost of trialling different control measures in the field was outside the scope of the project. Proposals to develop systems for evaporation mitigation should be developed and considered as essential within the research community.

Deep Drainage

This project has identified that significant volumes of water may be lost through deep drainage from on-farm storages, distribution systems and in-field application systems. In particular, the magnitude of the in-field deep drainage losses identified raise concerns regarding the traditional industry view that cracking clay soils do not "leak". The potential for groundwater rise and contamination due to deep drainage continues to be one fo the most significant environmental threats to the cotton industry. Hence, research should be continued to relation to the evaluation of the real economic and environmental impact of deep drainage across the industry.

The Development of Tools to Evaluate Alternative Irrigation Systems

The in-field irrigation evaluation tools (the "Irrimate" package) developed in conjunction with this project are currently being utilised by two irrigation engineering consultants to provide services to irrigators for irrigation efficiency improvement. The NCEA and these consultants propose continued development and promotion of this service. Further, the marriage of cotton irrigation engineering that utilises the Irrimate package with cotton irrigation agronomy that performs plant mapping and other more detailed agronomic services provides significant potential to push the agronomic and volumetric (or engineering) water use efficiency benchmarks for the Australian Cotton Industry. This "marriage" of services has commenced in a pilot form in both the Goondiwindi and Dalby regions with commercial pilot trials of this type of service (potentially 10 sites in both valleys for the upcoming 2001/2002 season).

Training and assessment protocols need to be developed to assist producers in making informed decisions regarding the deployment of alternative irrigation application systems (ie drip and low pressure mobile systems). The assessment and evaluation of these systems should be conducted in a manner which enables direct comparison of performance with best practice surface irrigation systems.

Data Collection for Other Regions

The data presented in this project is based on work in the Goondiwindi and Border Rivers region. This was due to directive from the CRDC Board that commissioned the project. This project has been heavily involved in supporting the establishment of WUE IDO's in both Queensland and New South Wales. Hence, it is expected that some system performance and benchmarking data will be collected from other regions by these government funded programs. However, where these programs do not provide an appropriate data for other regions, the industry should consider funding to ensure that a balanced picture of the industry performance is obtained. In addition, an evaluation of the design and management parameters identified in this project should be considered as part of the development process for new cotton areas (eg. Richmond and Ord).

11. Publications arising from the project

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Extension Posters (see Appendix 1)

- Water Storage Efficiency
- Distribution Channel Efficiency
- In-Field Application Efficiency
- Tailwater Recycling Efficiency
- Whole Farm Efficiency

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Appendix 1 – Extension Poster Publications

SYSTEM PERFORMANCE

ISSUES:

- Total Farm Performance
- Water Use Efficiency (WUE) Measures
  = Bales / ML
  = ML / Ha
  = $ / ML

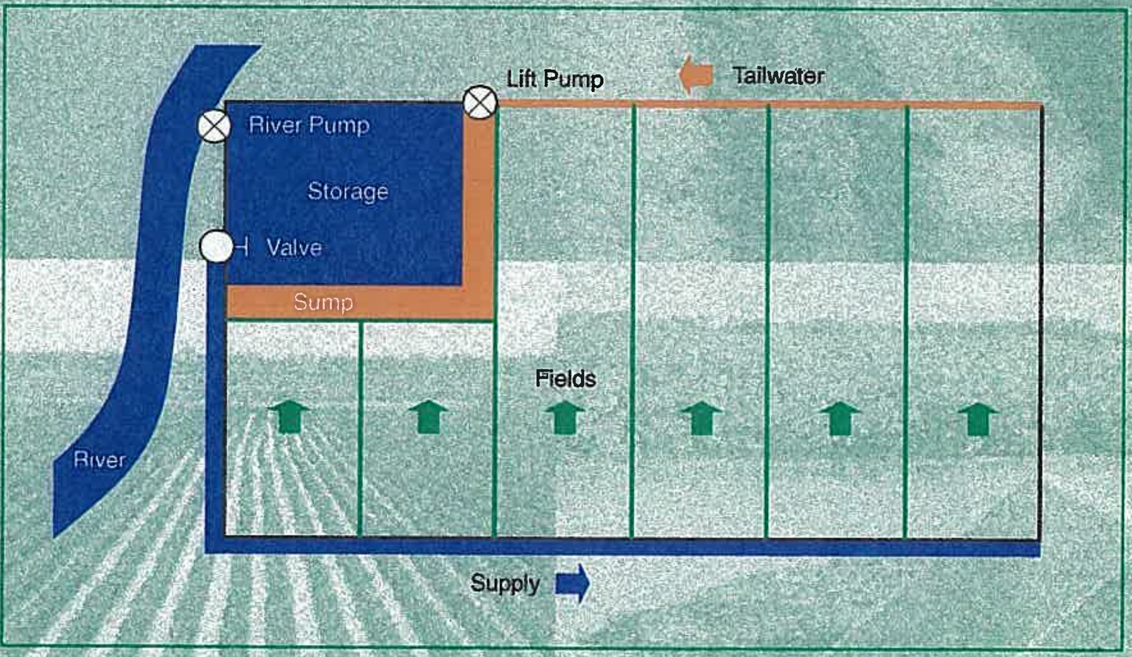
Cotton Irrigation Performance Benchmarks

Parameter	Range (Dependant on soil, climatic and agronomic conditions)	
Bales/ML	<1	>2
ML/HA	>9	<4.5
$/ML (Gross Return)	$200	$500

Whole Farm Efficiency = Storage Efficiency x Distribution efficiency x Application Efficiency

Benchmark data of whole farm use efficiency as measured in trial farms in the MacIntyre Valley region.

	Storage Efficiency %	Distribution Efficiency %	Application Efficiency %	Whole Farm Efficiency %
High	80	91	86	63
Low	55	86	71	34



TOOLS

- Best Management Practice Guidelines
- Effective Water Accounting System

NCEA

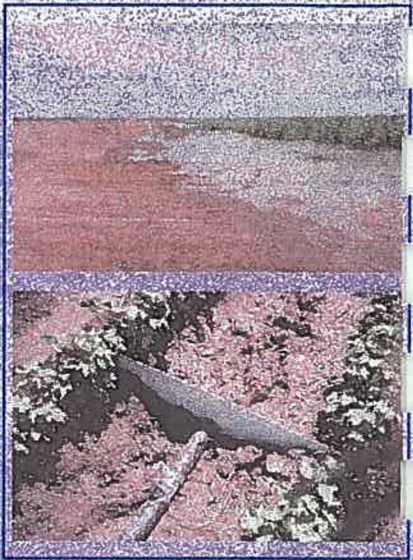
MEASURE, MONITOR MANAGE

Tools to Greater Water Use Efficiency (WUE)

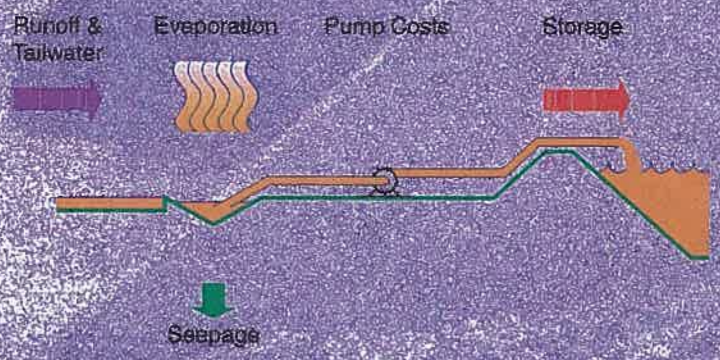
TAILWATER

ISSUES:

- Indicator of Water Logging Stress
- Deep Drainage Losses
- Relift Costs
- System Losses
- Operational Complexity



EVAPORATION: 1% (1 – 5%)



SEEPAGE: 3% (1 – 5%)

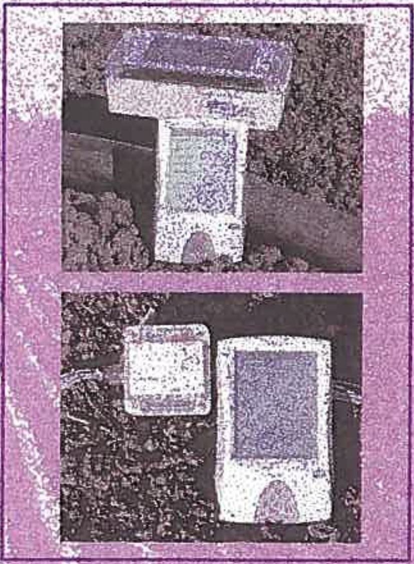
TOOLS

- Outflow Measurement
- "Full Stop" Deep Drainage Meters
- Soil Testing

INFIELD

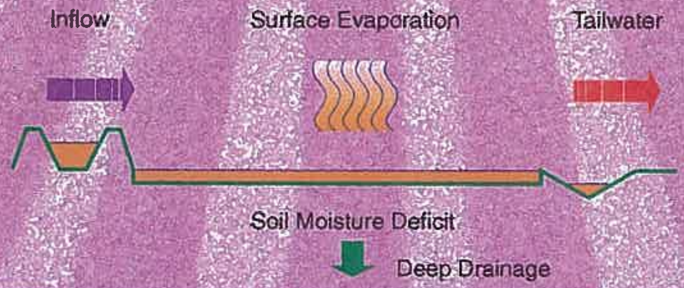
ISSUES:

- Scheduling
- Deficit
- Advance Rate
- Siphon Pull Time
- Flowrate In and Out



EVAPORATION: 2% (1 – 3%)

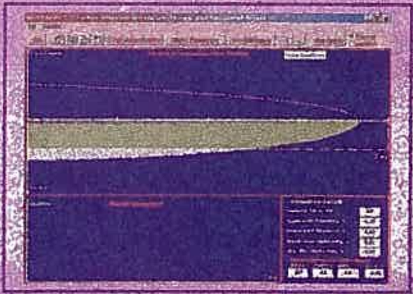
$$\text{Application Efficiency} = \frac{\text{Volume Applied to Deficit}}{\text{Volume Applied to Field}}$$



DEEP DRAINAGE: 10% (5 – 15%)

TOOLS

- Soil Moisture Measurement
- SIRMOD
- Irrimate Flow
- Irrimate Advance



NCEA

MEASURE, MONITOR MANAGE

Tools to Greater Water Use Efficiency (WUE)

Cotton Research and Development Corporation

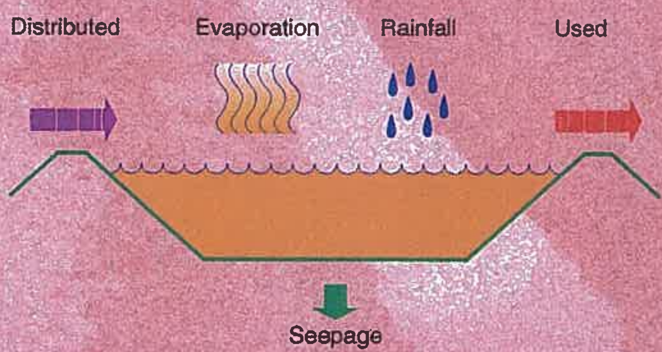
DISTRIBUTION

Issues:

- Evaporation
- Seepage
- Management

Evaporation: 3% (1 – 5%)

Distribution Efficiency = Volume Used / Volume Distributed



Seepage: 3% (1 – 5%)

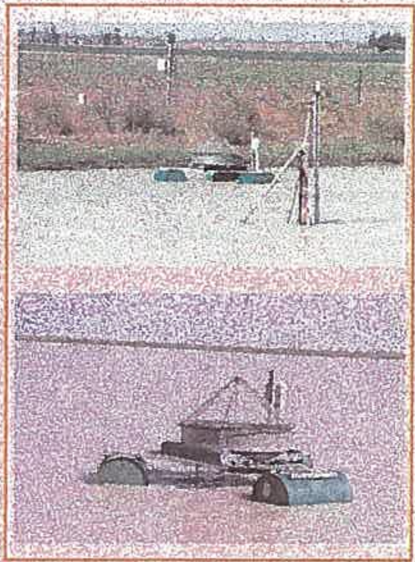
Tools

- Weather Station
- Flowrate
- Depth Measurement
- Automation

STORAGE

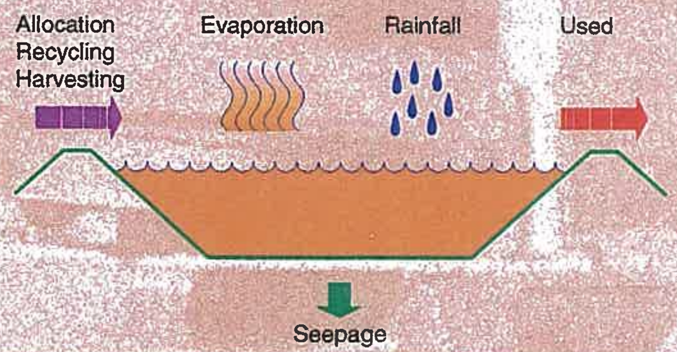
ISSUES:

- Evaporation
- Seepage
- Storage Management
- Storage Depth
- Flowrate in and out of dam



EVAPORATION: 30% (10 – 40%)

Storage Efficiency = Volume Used / Volume Stored



SEEPAGE: 5% (2 – 10%)

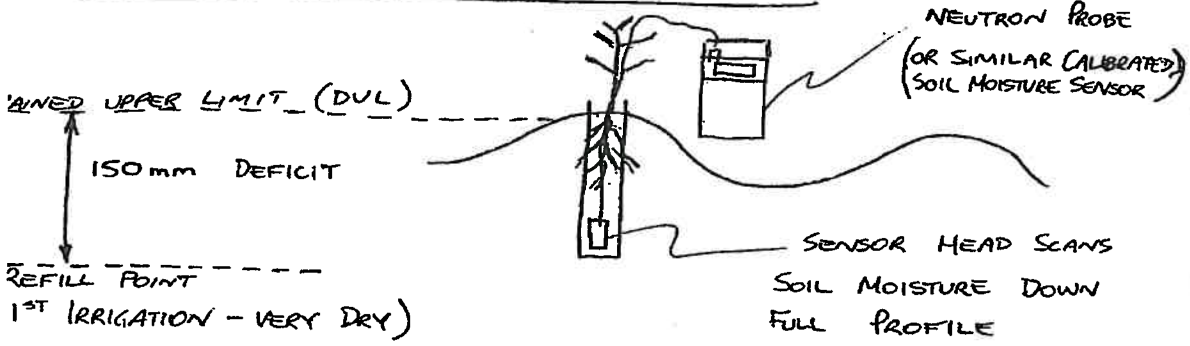
TOOLS

- Weather Station
- Flowrate
- Depth Measurement

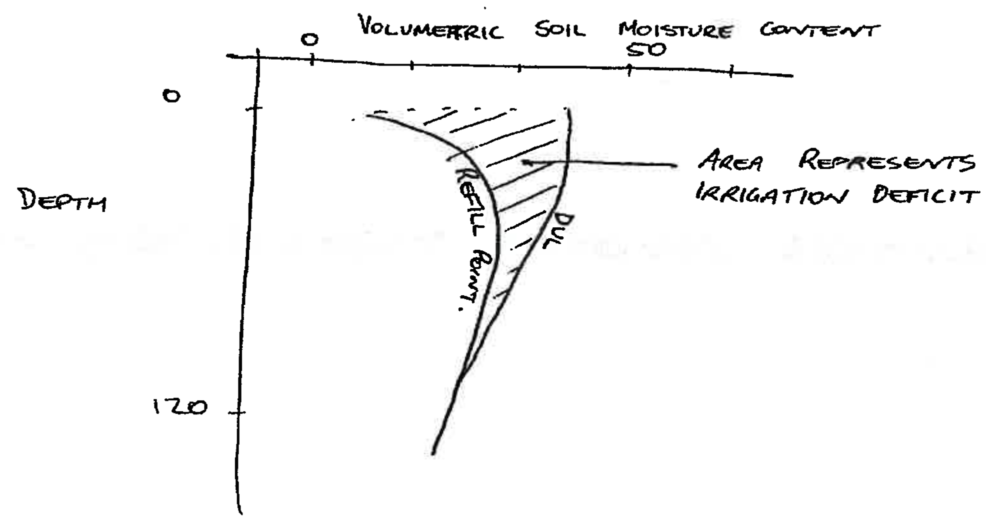
Appendix 2 - Measure it to Manage it Workshop Notes

MEASURING WATER REQUIRED OR.

2/ TARGET IRRIGATION (in millimetres)



EXAMPLE OF PROBE DATA

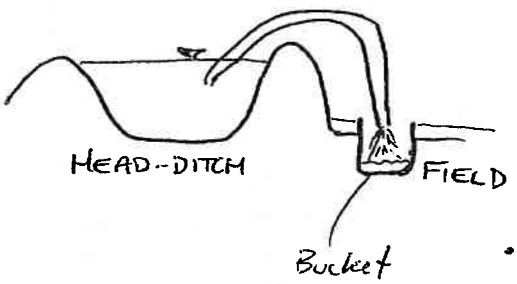


TARGET IRRIGATION = $\boxed{\quad}$ mm.

(ASSUMING FURROW IRRIGATION FILLS THE PROFILE TO DUL → TARGET IRRIGATION = WATER APPLIED TO ROOT ZONE)

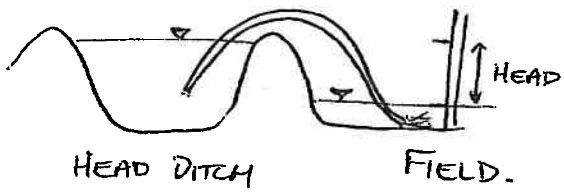
3. MEASURING WATER APPLIED

METHOD 1 :- BUCKET AND STOPWATCH



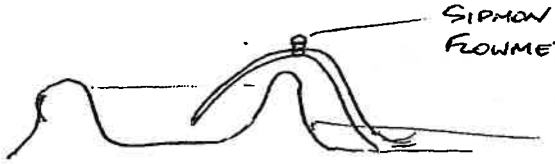
- RECORD THE TIME REQUIRED TO FILL A BUCKET OF KNOWN VOLUME
- FLOWRATE = $\dfrac{\text{VOLUME } (\ell)}{\text{TIME } (s)}$ (ℓ/s)
- FLOWRATE = $\boxed{}$ ℓ/s

METHOD 2 :- HEAD DISCHARGE CHARTS



- MEASURE THE HEAD BETWEEN THE HEAD DITCH AND FIELD
- READ OFF THE CHART THE FLOWRATE FOR THIS HEAD AND SIPHON SIZE
- FLOWRATE = $\boxed{}$ ℓ/s.

METHOD 3 :- SIPHON FLOW METER



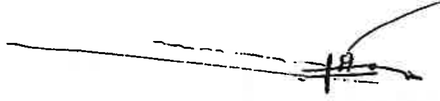
$$\text{FLOWRATE} = \boxed{}\ \ell/s$$

$$\text{WATER APPLIED (mm)} = \frac{\underset{(\ell/s)}{\text{FLOWRATE}} \times \underset{(sec)}{\text{TIME}}}{\text{AREA.}}$$

Area of field that water is applied

4. MEASURING TAILWATER

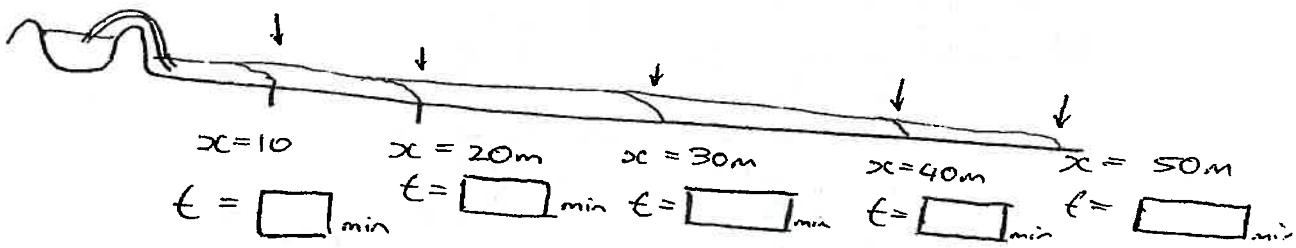
IF THE FURROW IRRIGATION SYSTEM RECYCLES TAILWATER THEN SUBTRACT THIS FROM WATER APPLIED



$$\text{TAILWATER} = \frac{\text{VOLUME } (\ell)}{\text{AREA } (m^2)} \ (mm)$$

5. USING IRRIGATION ADVANCE RATE AND MODELLING TOOLS TO SIMULATE IRRIGATION

MEASURE TIME FOR WATER TO REACH 10, 20, 30, 40, 50 m ALONG THE FIELD.



- USE "INFILT" TO CHARACTERISE INFILTRATION OF FURROW

- USE SIRMOD TO SIMULATE IRRIGATION.

Irrigation Record Sheet

Siphon Head/Discharge Table Method

Farm	
Field No.	

FIELD LENGTH (m)		[A]
ROTABUK SPACING (m)		[B]
NUMBER OF SIPHONS IN ROTABUK		[C]

Variety	
Soil Type	
Insect Pressure (No.sprays)	
Growth Regulator (No.sprays)	

Growth Regulator App Dates

CODE					[D]	[E]	[F]	[G]	[H]	[J]	[K]	
DATE	IRRIGATION No.	Ditch Head (mm) / Siphon Size		SIPHON LOCATION ALONG HEAD DITCH (top, middle, bottom)	Siphon Flow Rate (in litres/sec)	IRRIGATION START DATE:TIME	IRRIGATION FINISH DATE:TIME	DURATION TIME OF APPLICATION (in minutes)	APPLIED IRRIGATION (in millimetres depth of irrigation)	SOIL MOISTURE DEFICIT (mm)	IRRIGATION EFFICIENCY (%)	Crop Description / General Notes: ie Development Stage, Insect pressure etc
TOTAL FOR THE SEASON									mm	mm	%	
								EQUALS F - E	EQUALS (C x DxGx60) / (A X B)		CALCULATE (J/H)x100 %	

Yield		bales
Area		ha
		bales/ha

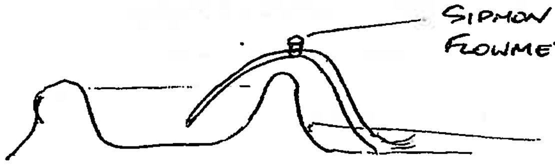
N.B. 100mm over 1ha = 1 ML.

Water Use		mm
		ML
		ML/ha
		ML/bale

Rainfall

Date	mm
Total	

METHOD 3: - SIPHON FLOW METER



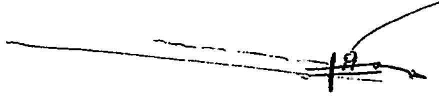
$$\text{FLOWRATE} = \boxed{} \ \ell/s.$$

$$\text{WATER APPLIED (mm)} = \frac{\overset{(\ell/s)}{\text{FLOWRATE}} \times \overset{(sec)}{\text{TIME}}}{\text{AREA.}}$$

Area of field that water is applied

4. MEASURING TAILWATER

IF THE FURROW IRRIGATION SYSTEM RECYCLES TAILWATER THEN SUBTRACT THIS FROM WATER APPLIED

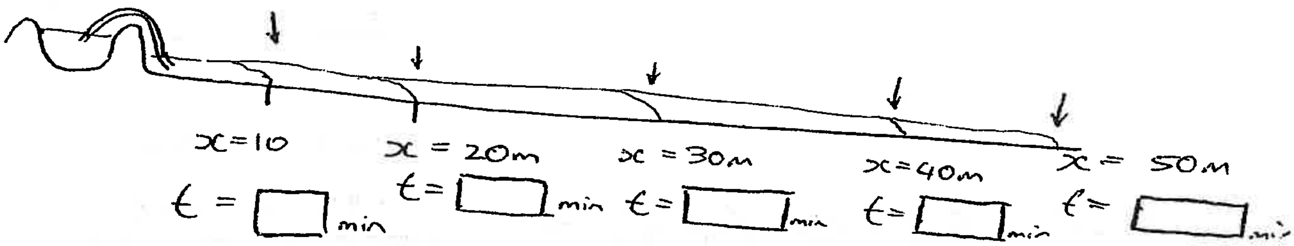


$$\text{TAILWATER} = \frac{\text{VOLUME } (\ell)}{\text{AREA } (m^2)} \ (mm)$$

5. USING IRRIGATION ADVANCE RATE AND MODELLING TOOLS TO SIMULATE IRRIGATION

MEASURE TIME FOR WATER TO REACH

10, 20, 30, 40, 50 m ALONG THE FIELD.



- USE "INFILT" TO CHARACTERISE INFILTRATION OF FURROW

- USE SIRMOD TO SIMULATE IRRIGATION.

Irrigation Record Sheet

Siphon Head/Discharge Table Method

Farm	
Field No.	

FIELD LENGTH (m)		[A]
ROTABUK SPACING (m)		[B]
NUMBER OF SIPHONS IN ROTABUK		[C]

Variety	
Soil Type	
Insect Pressure (No.sprays)	
Growth Regulator (No.sprays)	

Growth Regulator App Dates

CODE				[D]	[E]	[F]	[G]	[H]	[J]	[K]	
DATE	IRRIGATION No.	Ditch Head (mm) / Siphon Size	SIPHON LOCATION ALONG HEAD DITCH (top, middle, bottom)	Siphon Flow Rate (in litres/sec)	IRRIGATION START DATE:TIME	IRRIGATION FINISH DATE:TIME	DURATION TIME OF APPLICATION (in minutes)	APPLIED IRRIGATION (in millimetres depth of irrigation)	SOIL MOISTURE DEFICIT (mm)	IRRIGATION EFFICIENCY (%)	Crop Description / General Notes: ie Development Stage, Insect pressure etc
TOTAL FOR THE SEASON								mm	mm	%	
							EQUALS F - E	EQUALS (C x DxGx60) / (A X B)		CALCULATE (J/H)x100 %	

Yield		bales
Area		ha
		bales/ha

N.B. 100mm over 1ha = 1 ML.

Water Use		mm
		ML
		ML/ha
		ML/bale

Rainfall

Date	mm
Total	

Irrigation Record Sheet

Irrimate Method

Farm	
Field No.	

FIELD LENGTH (m)		[A]
ROTABUK SPACING (m)		[B]
NUMBER OF SIPHONS IN ROTABUK		[C]

Variety	
Soil Type	
Insect Pressure (No.sprays)	
Growth Regulator (No.sprays)	

Growth Regulator App Dates

CODE			[D]	[E]	[F]	[G]	[H]	[J]	[K]	
DATE	IRRIGATION No.	SIPHON LOCATION ALONG HEAD DITCH (top, middle, bottom)	VOLUME APPLIED (in litres)	IRRIGATION START DATE:TIME	IRRIGATION FINISH DATE:TIME	DURATION TIME OF APPLICATION (in minutes)	APPLIED IRRIGATION (in millimetres depth of irrigation)	SOIL MOISTURE DEFICIT (mm)	IRRIGATION EFFICIENCY (%)	Crop Description / General Notes: ie Development Stage, insect pressure etc
TOTAL FOR THE SEASON							mm	mm	%	
						EQUALS F - E	EQUALS (C x D) / (A X B)		CALCULATE (J/H)x100 %	

Yield		bales
Area		ha
		bales/ha

N.B. 100mm over 1ha = 1 ML.

Water Use		mm
		ML
		ML/ha
		ML/bale

Rainfall

Date	mm
Total	

IRRIGATION APPLICATION RECORDING SHEET

(using bucket and stopwatch method)

Farm		
Field No.		
Location of measurement		
Season		
FIELD LENGTH		[A]
ROTABUK SPACING		[B]
NUMBER OF SIPHONS IN ROTABUK		[C]

→ ACTION	RECORD	RECORD	MEASURE AND RECORD	MEASURE AND RECORD	CALCULATE (X / Y)	RECORD	RECORD	EQUALS E - F	EQUALS (C x D x G X 60) / (A X B)	RECORD	CALCULATE (J/H)x100 %
→ CODE			[X]	[Y]	[D]	[E]	[F]	[G]	[H]	[J]	[K]
DATE	IRRIGATION No.	SIPHON LOCATION ALONG HEAD DITCH (top, middle, bottom, or set 1, 2 or 3)	VOLUME OF BUCKET (in litres)	TIME TO FILL BUCKET (in secs)	SIPHON FLOWRATE (in litres per second)	IRRIGATION START DATE:TIME	IRRIGATION FINISH DATE:TIME	DURATION TIME OF APPLICATION (in minutes)	APPLIED IRRIGATION (in millimetres depth of irrigation)	SOIL MOISTURE DEFICIT FROM PROBE (in millimetres)	IRRIGATION EFFICIENCY (%)
TOTAL APPLIED TO FIELD FOR THE SEASON									mm	mm	%

Rainfall		Rainfall		Rainfall		Yield		bales
Date	mm	Date	mm	Date	mm	Area		ha
								bales/ha
TOTAL RAIN					mm			

Theoretical Siphon Flow in litres per second

Nominal Siphon Sizes (mm)	50	2 inch 51	2.5 inch 63	3 inch 75
Head (mm)				
100		1.79	2.15	2.89
110		1.88	2.26	3.03
120		1.96	2.36	3.16
130		2.04	2.45	3.29
140		2.12	2.54	3.41
150	2.09	2.19	2.63	3.53
160	2.16	2.26	2.72	3.65
170	2.23	2.33	2.80	3.76
180	2.29	2.40	2.88	3.87
190	2.36	2.47	2.96	3.98
200	2.42	2.53	3.04	4.08
210	2.48	2.59	3.12	4.18
220	2.54	2.65	3.19	4.28
230	2.59	2.71	3.26	4.38
240	2.65	2.77	3.33	4.47
250	2.70	2.83	3.40	4.56
260	2.76	2.88	3.47	4.65
270	2.81	2.94	3.53	4.74
280	2.86	2.99	3.60	4.83
290	2.91	3.05	3.66	4.91
300	2.96	3.10	3.72	5.00
310	3.01	3.15	3.79	5.08
320	3.06	3.20	3.85	5.16
330	3.11	3.25	3.91	5.24
340	3.15	3.30	3.97	5.32
350	3.20	3.35	4.02	5.40
360	3.24	3.39	4.08	5.47
370	3.29	3.44	4.14	5.55
380	3.33	3.49	4.19	5.62
390	3.38	3.53	4.25	5.70
400	3.42	3.58	4.30	5.77
410	3.46	3.62	4.35	5.84
420	3.50	3.67	4.41	5.91
430	3.55	3.71	4.46	5.98
440	3.59	3.75	4.51	6.05
450	3.63	3.79	4.56	6.12
460	3.67	3.84	4.61	6.19
470	3.71	3.88	4.66	6.26
480	3.75	3.92	4.71	6.32
490	3.79	3.96	4.76	6.39
500	3.82	4.00	4.81	6.45
510	3.86	4.04	4.86	6.52
520	3.90	4.08	4.90	6.58
530	3.94	4.12	4.95	6.64
540	3.97	4.16	5.00	6.70
550	4.01	4.20	5.04	6.77

Nominal Siphon Sizes (mm)	50	2 inch 51	2.5 inch 63	3 inch 75
Head (mm)				
560	4.05	4.23	5.09	6.83
570	4.08	4.27	5.13	6.89
580	4.12	4.31	5.18	6.95
590	4.15	4.35	5.22	7.01
600	4.19	4.38	5.27	7.07
610	4.22	4.42	5.31	7.13
620	4.26	4.45	5.35	7.18
630	4.29	4.49	5.40	7.24
640	4.33	4.53	5.44	7.30
650	4.36	4.56	5.48	7.36
660	4.39	4.60	5.52	7.41
670	4.43	4.63	5.57	7.47
680	4.46	4.66	5.61	7.52
690	4.49	4.70	5.65	7.58
700	4.52	4.73	5.69	7.63
710	4.56	4.77	5.73	7.69
720	4.59	4.80	5.77	7.74
730	4.62	4.83	5.81	7.80
740	4.65	4.87	5.85	7.85
750	4.68	4.90	5.89	7.90
760	4.71	4.93	5.93	7.95
770	4.74	4.96	5.97	8.01
780	4.78	5.00	6.01	8.06
790	4.81	5.03	6.04	8.11
800	4.84	5.06	6.08	8.16
810	4.87	5.09	6.12	8.21
820	4.90	5.12	6.16	8.26
830	4.93	5.15	6.20	8.31
840	4.96	5.18	6.23	8.36
850	4.99	5.22	6.27	8.41
860	5.01	5.25	6.31	8.46
870	5.04	5.28	6.34	8.51
880	5.07	5.31	6.38	8.56
890	5.10	5.34	6.42	8.61
900	5.13	5.37	6.45	8.66
910	5.16	5.40	6.49	8.70
920	5.19	5.43	6.52	8.75
930	5.21	5.46	6.56	8.80
940	5.24	5.48	6.59	8.85
950	5.27	5.51	6.63	8.89
960	5.30	5.54	6.66	8.94
970	5.33	5.57	6.70	8.99
980	5.35	5.60	6.73	9.03
990	5.38	5.63	6.77	9.08
1000	5.41	5.66	6.80	9.12

Nominal siphon length = 4 metres
To get Imperial GPH multiply by 800 (793)