

Fitzroy Basin Association – Neighbourhood Catchment Program

Increasing the sustainability and efficiency of irrigated agriculture in the Dawson Valley Irrigation Area

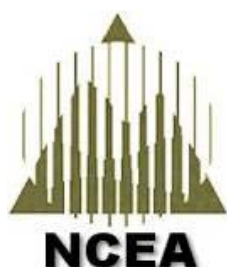
Final Report

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Executive Summary

The Dawson Valley Irrigation Area (DVIA) was developed in the 1920's and now predominantly produces cotton. Many of the irrigated farms in the area have traditionally relied on water supplied by the irrigation scheme and have or can not harvest runoff from on-farm rainfall events or irrigation tailwater. This is becoming atypical in the Australian cotton industry as harvesting this runoff provides a ready water source and prevents the transport of sediments, nutrients and chemicals off farm. There are currently a range of issues affecting the future of the DVIA, one is the inability to contain storm events, potentially leading to environmental impacts. This project was funded by the Fitzroy Basin Association as part of the National Action Plan on Salinity and Water Quality to identify strategies to improve the performance and sustainability of irrigation practices within the DVIA and local area.

This project was conducted over a three year period from 2004-2007 on farms adjacent to the Dawson River (south of Theodore) and in the DVIA at Theodore, Queensland. To achieve the expected outcomes the project was delineated into three activities: Intensive field monitoring trial site comparing current (Control) and improved (Treatment) irrigation performance and runoff water quality from two fields. Regional remote sensing of crop vigour on farms that could perhaps benefit from irrigation assessment and optimisation conducted by local agronomists. Case studies on irrigation performance and improvement on selected fields with concurrent capacity building of the local agronomists in the Irrimate irrigation performance tool kit. However the limited water allocation and the lack of early season rainfall in the final year severely limited confirmatory activities, in that the majority of cotton crops in the DVIA were ploughed in due to the lack of water.

Soil moisture deficit were largely exceeded in early season irrigation events by the application volume, giving rise to limited buffering capacity in the soil to accept rainfall events and the possible losses to runoff and deep drainage. Latter irrigations, especially those in the second season, rectified the problem. The lack of irrigation water in the final season highlighted the need to match deficit and applied water for all events, so that maximum water is conserved for future irrigation events. A comparison of seasonal water balances in 2004/05 with 2005/06 was indicative of the minimum crop water use requirements of cotton and the adverse impact of inopportune rainfall on wet soil. The current irrigation practices during the first season generated considerable losses from both irrigation and rainfall. Irrigation volume in the final season of 2006/07 was similar to the previous season, however the distribution of it across the irrigation events needed to be perfect under the conditions, because rainfall was largely confined to late January and February and thus provided little to no benefit for the crop.

Irrigation efficiencies were not markedly different at the intensive trial site even though the application flow rate on the treatment site was twice that of the control and irrigation run time less than half the of the control. The response of the soils along the river to irrigation is different for fast or slow irrigations, in that under fast irrigations final infiltration rates remain high through large crack fill. On the other hand slow irrigations final infiltration rates are limited on a slowly permeable soil that tends to consolidate as cracks close ahead of the advancing irrigation water. However on fields in the DVIA irrigation application efficiencies were dramatically improved from ~70 to ~90% by simply reducing time to cut-off by 3hours on average. Flow rates were not modified as they were reasonably high in the first instance (>3L/s an average). The overall infiltration characteristic data highlighted the poor correlation between the period of irrigation and total infiltration.

The concentration of chemicals in the runoff water was higher for the treatment site compared to that of the control site at lower flow rates. The time to irrigation cut-off becomes increasingly important as flow rates increase to ensure runoff is not generated causing significant off site movement of nutrients, chemicals and soil. Gross production water use efficiency (GPWUI) of 1.56b/ML was well above industry standards (1b/ML) for both treatments in the second season because of the minimal water use and very good yields in comparison to the other years. The first season GPWUI was low at 0.51b/ML, while the final season even under limited water conditions was reasonable at 1.2b/ML. Although the volume of irrigation water applied was similar to that of the previous year the individual irrigation application volumes and corresponding deficits of the final year were distinctly different. The over irrigation in the first three events reduced available water for later in the season thus crop water requirements could not be met. Effective GPWUI was equivalent for both sites at approximately 1.42 bales/ML. Although overall yield was similar for both sites the infield variability was distinctly different in that the Treatment site had a more consistent crop from top to bottom of the field.

Individual case studies on two farms on the Dawson River highlighted the efficiencies that have been achieved under current practices. On both properties application efficiencies and distribution uniformities exceeded 85% and hence did not require further optimisation. A whole of field variability case study demonstrated that by combining accurate infiltration curves and simple single advance point measurements it was possible to predict the infiltration curves across the entire field. Some of the variation in the field was explained by soil compaction of machinery traffic and variation in inflow rates could explain some of the remainder variation. Although maximum benefit can be gained by whole of field irrigation performance assessment it is not done routinely and not practical with the current suite of monitoring tools. Overall farms in the DVIA and along the river could improve irrigation performance by largely reducing the time to cut-off, thus minimising runoff and deep drainage. Further optimisation would be achieved by increasing inflow rates and modifying the infiltration characteristic. To modify the infiltration characteristic would require monitoring and manipulation of the soil water deficit prior to an irrigation event and then match the applied volume to that deficit to either achieve a full profile, a deficit condition to capture rainfall, or generate a leaching requirement. Strategies developed from the guidelines outlined in the document were not tested because of the limited cropping in the DVIA in 2006/07 season. The strategies were:

1. Compare total inflow and target deficit. An application in excess of the target deficit indicates potential run-off or deep drainage, or both.
2. Analyse soil moisture data to investigate wetting and extraction patterns, waterlogging and readily available water.
3. Investigate commercial analysis and modelling services
4. Modify infiltration characteristics (deficit), inflow rates and or TCO (<500 minutes) to achieve acceptable E_A (>85%) and DU (>90%).
5. Set irrigation management strategies to operate: a “no runoff” scenario, and a deficit irrigation strategy to capture a percentage of incrop rainfall.

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1. Introduction

The Dawson Valley Irrigation Area (DVIA) was developed in the 1920's and now predominantly produces cotton. Irrigation is almost entirely undertaken using furrow methods on predominantly black Vertisol clay soils. Many of the irrigated farms in the area have traditionally relied on water supplied by the irrigation scheme and have not harvested runoff from on-farm rainfall events or irrigation tailwater. This is becoming atypical in the Australian cotton industry as harvesting this runoff provides a ready water source and prevents the transport of sediments, nutrients and chemicals off farm. There are currently a range of issues affecting the future of the DVIA:

- Recent drought and potential climate variability have influenced the supply and security of water. The extent of this impact was initially realised during the 2002-03 summer irrigation season, and most recently in the 2006-07 season, when many crops ran short of water.
- Fitzroy Basin Water Resource Plan and Resource Operation Plans have now been implemented.
- The current irrigation scheme lacks the ability to contain storm events, potentially leading to environmental impacts.
- Sunwater has periodically proposed a redesign of the irrigation scheme which may have significant impacts on the DVIA irrigation enterprises.
- Recent Rural Water Use Efficiency Trials have indicated the potential to improve current furrow irrigation procedures with possible outcomes including less deep drainage, shorter periods of crop waterlogging and decreased water use.
- The Central Queensland Strategy for Sustainability 2 has now been released with targets and actions including increased water use efficiency, salinity and deep drainage minimisation, stormwater recycling and sustainable production and development.

Given the range of issues affecting the DVIA, there has been discussion regarding the potential to redevelop the irrigation scheme. If this were to occur, it would be important that this redevelopment was able to efficiently handle any potential shift in furrow irrigation management strategies or irrigation application system change. The redesign of the scheme may also include consideration of ownership redistribution to aggregate the currently scattered land holdings. This would be expected to have impacts on whole farm water management systems and irrigation strategies.

Rural Water Use Efficiency Initiative (RWUEI) activities conducted on farms within the DVIA between 2000 and 2003 indicated the potential to improve the performance of irrigation practices in the region. Specifically, the RWUEI trials highlighted:

- excessive periods of crop waterlogging, leading to yield decline and sub-optimal conversion of irrigation water to crop production;
- the occurrence of deep drainage during irrigation events, although volumes have not been estimated;
- greater movement and infiltration of soil water than previously recognised which indicates the potential for different application management strategies;
- application of irrigation water in excess of that required by the crop and greater than may be delivered through improved application techniques; and

- scheduling practices that may be improved through greater use of objective scheduling techniques and better integration of agronomic requirements and system delivery logistics.

This project was funded by the Fitzroy Basin Association as part of the National Action Plan on Salinity and Water Quality to identify strategies to improve the performance and sustainability of irrigation practices within the DVIA and local area. The specific aims were to develop improved methods for:

- (a) Applying irrigation water to crops within the DVIA, minimising both the duration of waterlogging and the volume of deep drainage. Additionally, changes to the volume and quality of run-off would result in improved water use efficiency and reduced environmental impact, and
- (b) Scheduling irrigations based on both crop water requirements and application system logistics would ensure maximum seasonal water use efficiency and more sustainable production. Of importance was increased ability to capture rainfall and progression towards stormwater containment strategies.

The expected outcomes of the project were:

1. Demonstrated potential for improvements in irrigation performance including water savings, reduced deep drainage and runoff volumes and total contaminant export and possible production benefits. Estimated targets maybe 10% increase in WUE, 20% decrease in DD and runoff volumes, and associated reduction in contaminants.
2. Benefits including a reduction in unsustainable land management practices, development of more sustainable production systems, reduced likelihood of irrigated salinity and greater enterprise viability including increased capacity to pay for improved NRM.
3. Approximately 90% awareness of the project and the guidelines, procedures and tools developed with the expectation that this may translate to high rates of adoption and consequent regional benefits.
4. Increased capacity of both growers and consultants to understand the need, justification and ability to undertake change.

2. Methodology

This project was conducted over a three year period from 2004-2007 on farms adjacent to the Dawson River (south of Theodore) and in the Dawson Valley Irrigation Scheme Area (DVIA) at Theodore, Queensland. To achieve the expected outcomes the project was delineated into three activities:

- Intensive field monitoring trial site which was designed to compare current irrigation performance with improved management and to develop guidelines and strategies that could be used in the wider irrigation area to enhance sustainability of the DVIA.
- Regional remote sensing of crop vigour was utilised to determine if a linkage existed between that and irrigation performance. The resultant analysis was used to determine which fields on which farms could perhaps benefit from irrigation assessment and optimisation. Local agronomists were engaged to conduct the assessments and extend the improvements in efficiency concepts underwritten in the project.
- Case studies on irrigation performance and improvement were also conducted on selected fields to demonstrate irrigation performance improvements and associated the extension methodology. The concurrent capacity building of the local agronomists was an integral part of the project, which incorporated the use of the Irrimate irrigation performance tool kit. The agronomists were trained and supported in its use and data analysis. The agronomists deployed the Irrimate system on the farms that had variable vigour determined from remote sensing. Further case studies were conducted on the intensive site to determine the spatial variability that exists in furrow irrigation systems

2.1 Intensive field monitoring trial

An intensive field scale monitoring trial was initiated on a furrow irrigated farm (Lagoona) situated on the Dawson River (25⁰ 08' 36''S 150⁰ 09' 43''E) 30 km south of Theodore township. The predominant soil on the site was an alluvial Black Earth (i.e. Black Vertosol) locally known as a *Coolibah* soil profile class. The plant available water capacities (PAWC) and readily available water (RAW) for this soil and other local soils in the Theodore district are shown in Table 1. The trial sites were located within a closed irrigation system with considerable capacity to capture runoff for recycling. Hence, off-site movement of nutrients and chemicals generated as a result of the irrigation management trials were contained within the farm boundary.

Table 1. Plant available water capacity (PAWC) estimated from a wide range of similar soil types in this and other regions by Qld Dept natural resources and Water. Nominal readily available water (RAW) (mm of water per m of soil depth) in soils of the Theodore District, Central Queensland. Soil map of the immediate Theodore area is at Appendix 2.

Soil Type	Map Code	PAWC (mm/m)	RAW (mm/m) ¹
Coolibah	C	178	89
Dakenba	D	219	110
Duaringa	DU	87	44
Eurombah	E	207	104
Juandah	J	201	101
Kiddell	K	169	85
Kroombit	Km	219	110
Malakoff	Mf	186	93
Thomby	T	150	75
Wandoan	W	207	104

¹ Nominally equal to 0.5 x PAWC

This trial compared a traditionally managed furrow irrigation field with an improved furrow irrigation field with management optimised using the irrigation performance assessment tool Irrimate™ and the integral SIRMOD analysis software. The main difference in management between the traditional and improved fields was the irrigation opportunity time. Opportunity time is the length of time that irrigation water is applied to the soil surface and is available for infiltration. Opportunity time is calculated as the difference in time between when irrigation water first reaches a point in the field (i.e. advance time) and when the last surface water drains from that point (i.e. recession time) after irrigation. The trial fields were located within a closed irrigation system with considerable capacity to capture runoff for recycling. Hence, off-site movement of nutrients and chemicals generated as a result of the irrigation management trials were contained within the farm boundary.

The traditionally managed field (termed the “Control”) was irrigated using single 50 mm siphons (applied to alternate furrows) to deliver ~2 L/s/furrow for up to 16 hours (extended opportunity time). The improved irrigation management system (termed the “Treatment”) used two 50 mm siphons in each furrow during the first season and 75 mm siphons (applied as alternate furrow) in the following seasons to deliver 4.5 to 6 L/s/furrow for up to 6 hours (reduced opportunity time). The trial was conducted on irregular shaped fields in the first and second years. However, these fields were reconfigured into two symmetric fields for the third year to improve irrigation comparisons and data acquisition. A local consultant managed the collection of yield, crop performance and cotton quality data and conducted the infield irrigation assessments.

Measurements of applied and runoff water quality and quantity, which allowed a comparison between existing and improved irrigation practices, were measured by using a STARFLOW Doppler meter mounted within the inlet pipe upstream of the supply head ditch. This system logged the flow velocity and area of flow at five minute intervals during irrigation events. An Irrimate™ siphon flow meter was also installed in one of the evaluation furrows. The whole field and single furrow inflow hydrographs did not exhibit any significant temporal changes during the irrigation events and hence, a constant inflow assumption was used in the subsequent performance analyses. A number of siphon head measurements were also collected and the discharge was estimated using the procedure explained by Bos (1979). The resulting inflow rates were found to be in close agreement with the inflow measured using the STARFLOW meter. Water level in the supply channel was measured by pressure sensing transducers and local weather conditions were monitored by a Measurement Engineering Australia weather station.

Deep drainage was estimated by difference, through a combination of water balance and SIRMOD modelling of runoff. Soil moisture deficits were estimated from daily ET_o values and converted to crop water use (crop evapotranspiration (ET_c)) by utilising accumulated heat units after planting (HUAP) and cotton growth stages to determine local crop factors (K_c) (Table 2). Enviroscan capacitance probes and known plant available water capacities (PAWC) of local soils (Table 1) were also used for irrigation scheduling. The available soil moisture at the start and end of the season were considered to be similar and were not included in the seasonal water balance calculations.

Water quality samples from field outflows were collected using an ISCO3700 automated pumping sampler. Furrow runoff discharged into stainless steel containers located at the end of the two furrow irrigation sections. Teflon sampling tubes and suction lines at the base of the container transferred the samples to the pumping sampler. Within 6 hours of capture, collected samples were stored at 4°C in a cool room before detailed analysis. The samples were analysed for sediment concentration, nutrients (e.g. nitrogen and phosphorus), insecticides (e.g. endosulfan and dimethoate) and herbicides (e.g. atrazin, diuron,

fluometuron, simazin, trifluralin, and prometryn). Nitrogen, phosphorus, potassium and other chemicals were analysed in an Australian accredited laboratory following the methods outlined in Water for Analytical Laboratory Use - Specification and Test Methods First Edition; (CEN EN ISO 3696: 1995) developed by the International Organisation for Standardization USA. Total pollutants loads were calculated based on the sample concentrations and measured runoff volume from the fields.

Table 2. Crop coefficients used for estimating daily crop water use and soil moisture deficit for cotton grown in Central Queensland for each growth stage and accumulated heat units after planting

Cotton Growth Stage	Days from Planting	Heat Units After Planting (HUAP)	Crop Coefficient (Kc)
Seeding	0		
Emergence	7	60	0.35
1 st Square	36	450	0.55
Mid Squaring	46	600	0.75
1 st flower	56	732	0.95
50%flower	64	855	1.15
Max Flower	72	960	1.20
1 st open boll	102	1430	1.20
Open bolls - 25%	111	1580	0.83
Open bolls - 50%	120	1710	0.64
Open bolls - 95%	133	1905	0.50
Defoliation	155	2260	
Harvest	167	2430	

Outflow volume was measured using a STARFLOW Doppler meter mounted within the outlet pipe downstream of the tail drain. Area of flow and flow velocity were logged at five minute intervals during irrigation events. However, mounting the instrument on the pipe wall to avoid being buried by siltation resulted in inferior data and significant data losses. Runoff volumes from the control site were skewed toward shorter furrows which would be expected to over-estimate the offsite movement of chemicals and sediment from the whole site. Hence there was a significance reliance on SIRMOD analysis to provide whole of field estimates of runoff and deep drainage. However, extrapolating the SIRMOD analyses to whole of field response involved assuming that all furrows were of equal length and that the infiltration characteristics were homogenous across the field. Hence, whole field runoff would be expected to be slightly underestimated for the actual field conditions (i.e. irregularly shaped fields) at Lagoona during the first two seasons.

SIRMOD analysis was also used to determine irrigation Distribution Uniformity (DU) and Application Efficiency (E_a). DU relates to the evenness of irrigation application. However, it does not account for over irrigation. E_a is the ratio of the water that is available to the plant compared with that delivered to the field. The higher the efficiency, the greater proportion of applied water that is available to the crop, indicating less deep drainage and runoff and a lower likelihood of water borne contaminants.

2.2 Regional analysis of infield crop variation due to irrigation and field optimisation trials

Regional satellite imagery was used to evaluate the effect of surface irrigation management practices on variations in crop production within fields. Satellite imagery of the entire irrigation district taken during 2004-05 at a resolution to enable individual field evaluations was used to determine if there was any systematic variation in crop vigour across fields. Normalized Difference Vegetation Index (NDVI) images were displayed in a rainbow scheme (i.e. blue through green, yellow and red). Higher NDVI values indicated higher vigour/biomass due to an increased "greenness" or density of vegetation. Whilst vigour

mapping highlights variations in crop growth due to a number of factors, variations due to poor surface irrigation practice are generally systematic in their representation and can often be readily identified. These regional vigour maps were used to identify spatial irrigation performance benchmarks and, more importantly, allow specific areas of poor performance to be identified and addressed.

The NDVI images were used to select five farms within the DVIA (56° 50'S and 150° 06' 24'E) which showed systematic crop vigour variation which appeared to be related to irrigation performance. These sites were subjected to irrigation performance evaluations during 2005-06 and strategies to improve the irrigation performance were identified and implemented in 2006-07. Collection of Irrimate™ furrow irrigation performance and water quality data on these sites were conducted by the local agronomic consultants who were normally engaged by the property owners. The Irrimate™ performance assessment on these fields was used to identify the uniformity of irrigation application. Water quality samples were analysed as above. However, follow-up evaluations of crop vigour uniformity using NDVI imagery in the 2006-07 season using ground based sensor units was not possible due to the lack of water for irrigation and crop failure.

2.3 Case studies of irrigation performance

The project relied heavily on the Irrimate™ surface irrigation performance assessment tools. Irrimate™ irrigation evaluations were used to provide farmers with information about the uniformity and efficiency of their furrow irrigation applications. To extend the use of the tool beyond the intensive research site (section 2.1) and to build capacity within the local commercial consultant sector, the local consultants were trained in the use of the Irrimate™ tools. Project assistance was also provided to enable the local consultants prepare case studies on local farms which demonstrated the benefits of irrigation performance monitoring and optimisation.

Under the Irrimate™ agreement, Certified Level 1 consultants analyse the irrigation monitoring data and provide feedback to clients. In order to build the local skills and capacity of consultants, irrigation data collected by the local consultants from two case study sites were analysed by Sustainable Irrigation Systems (a Registered Level 1 Irrimate™ service provider). This analysis was provided to the local consultant agronomists and their clients.

An additional intensive field trial was also conducted on Lagoona to quantify the variability in infiltration across a field and the impact of this variation on whole field irrigation performance. Detailed advance and runoff measurements from a small number (i.e. less than eight) of furrows are normally used with the Infiltration Parameter from Advance and Runoff Model (IPARM) to estimate the infiltration characteristics of the soil. A new procedure was used to predict the infiltration parameters based on completion times for a large number (i.e. ~ 50) of furrows. The resulting data set provided an opportunity to evaluate the application of whole field evaluation probability techniques for field scale optimisation of furrow irrigation.

3. Results

3.1 Intensive field monitoring trial

3.1.1 Soil Moisture Deficit

The trial fields received considerable rainfall during the 2004-05 season (Figures 1). In all but five instances (late November and early February), the volume of rainfall exceeded the soil moisture deficit by 3 to 43 mm (average = 18 mm).

Infiltrated irrigation volumes at the Control site (Figure 1a) were poorly matched to the calculated soil moisture deficit during the first two months and fell short of the deficit by 11 mm on average (range = 4 to 18 mm) during the later phase of the season. At the Treatment site (Figure 1b), all but one of the irrigation volumes exceeded the measured soil moisture deficit. Excluding the single event when application volume was less than the deficit, excess irrigation volumes ranged from 15.6 to 78 mm (average = 37.6 mm).

The re-irrigation deficit was generally less than the assumed readily available water content (89 mm) for the soil (Table 1). For the irrigation events occurring more than 50 days after planting, the difference between the soil moisture deficits (calculated using the crop coefficients Table 2 and ET_0) and the assumed refill point (RAW) of 89 mm (Figures 1a&b) ranged from 17 to 44 mm (average = 31.8 mm) for the Control site and 17 to 54 mm (average = 38.6mm) for the Treatment site.

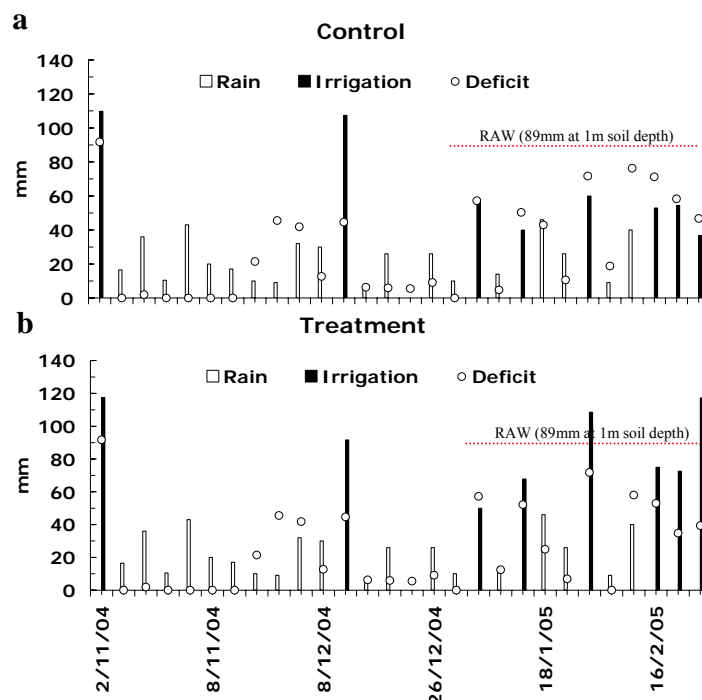


Figure 1. ETC based soil moisture deficit, infiltrated irrigation water and in-crop rainfall for the (a) Control and (b) Treatment fields during the 2004-05 cotton season. Including the nominal RAW assuming an active root zone of 1m.

The rainfall during the second season (2005-06) was considerably different from the first season in that there were 50% fewer events. Three rainfall events matched the deficit, four exceeded the soil moisture deficit and three made little impact on it (Figure 2). The irrigation

applications in the Control were closely matched the calculated deficit (Figure 2a), with one exception on the 11/12/05. However, with one exception, the average infiltrated irrigation volumes for the Treatment site (Figure 2b) exceeded the calculated deficit by between 4 and 27 mm (average = 14 mm). For the irrigation events occurring more than 50 days after planting, the difference between the calculated soil moisture deficit and the assumed refill point of 89 mm ranged from 29 to 64 mm (average = 53 mm) for the Control site (Figure 2a) and 29 to 71 mm (average = 56 mm) for the Treatment site (Figure 2b).

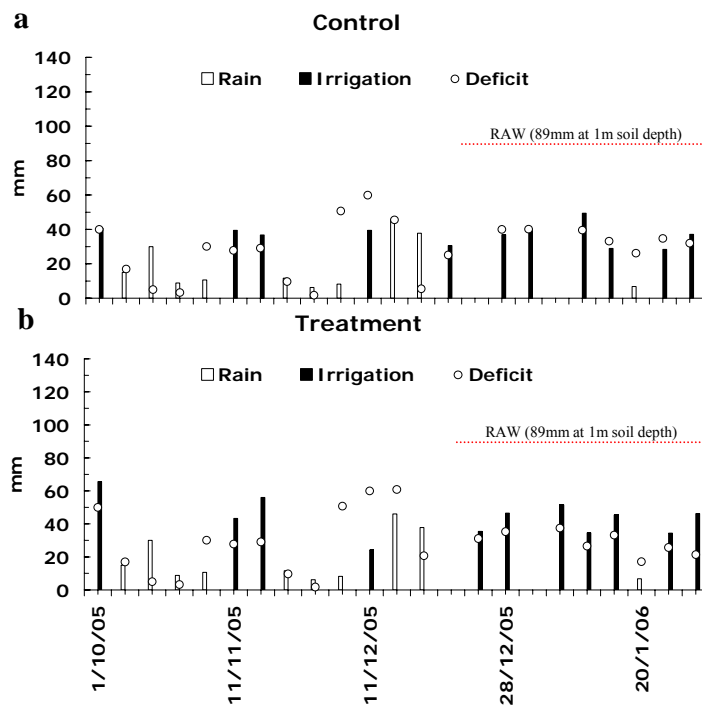


Figure 2. ET_c based soil moisture deficit, infiltrated irrigation water and in-crop rainfall for the (a) Control and (b) Treatment fields during the 2005-06 cotton season. Including the nominal RAW assuming an active root zone of 1m.

The third season (2006-07) rainfall was considerably lower than during the previous seasons as there were only six effective rainfall events. The two early season rainfall events applied an amount similar to the soil moisture deficit (Figure 3). However, the later season rainfall events did not satisfy the large soil moisture deficit which accrued at the end of the season due to insufficient irrigation water.

The volume of water applied by the first three irrigation events exceeded the calculated soil moisture deficit by 21, 45, 14 mm and 30, 50, 18 mm for the Control and Treatment sites, respectively (Figure 3). The late season irrigation volumes were poorly matched to soil moisture deficits falling well short of the soil requirement by 8, 24, 29 and 13, 32, 24 mm for the Control and Treatment sites, respectively.

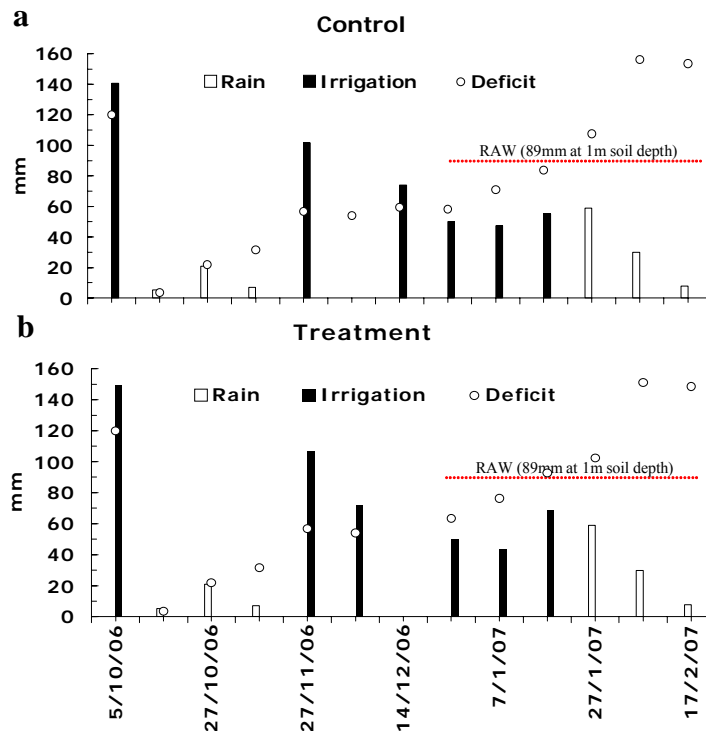


Figure 3. ET_c based soil moisture deficit, infiltrated irrigation water and in-crop rainfall for the (a) Control and (b) Treatment fields during the 2006-07 cotton season. Including the nominal RAW assuming an active root zone of 1m.

3.1.2 Water balance

More water was applied to the Control site (845 mm) compared with the Treatment site (771 mm) during 2004-05 (Figure 4). The seasonal water balance for the 2004-05 cotton season indicated considerable losses of irrigation water to runoff (325 mm) and deep drainage (101 mm) for the Control site. The Treatment site had lower run-off (79 mm or 9 % of applied water) but higher deep drainage (251 mm or 33 % of applied water). However approximately 50 % of total rainfall was not effective with 241 and 228 mm lost at the Control and Treatment sites, respectively (Figure 4).

The seasonal water balance for 2005-06 showed that the water losses were lower than in the previous season. Applied irrigation volumes closely matched crop requirements (525 mm), maintaining deep drainage and runoff for both sites at acceptable levels (Figure 5). The loss below the active root zone as a result of over irrigation in the Treatment site (Figure 2b) was 16 % of applied water, where as deep drainage losses in the Control site were less than 4 %. However, the Treatment site lost 10 % of the applied irrigation water to runoff while the Control site lost 23 %. Rainfall fell during periods of high soil moisture deficit (Figure 2). Hence, rainfall losses were 23 % at the Treatment site and 31 % for the Control site.

There were six irrigation events during the 2006-07 season (Figure 3) compared with eight and eleven during the previous seasons. Although total irrigation volumes were similar to the earlier seasons, supplementary rainfall was distinctly different. However, estimated seasonal water balance losses for irrigations were still considerable (Figure 6). Effective in-crop rainfall was less than 130 mm, all of which occurred under high deficit conditions (Figure 3) resulting in ~4 % rainfall loss. Runoff losses from irrigation were 5.7 % and 7.7% of applied

water for the Control and Treatment sites, respectively. Deep drainage losses only occurred during the first three irrigations of the season (Figure 3). A total of 59 mm of deep drainage (i.e. 11.6 % of the applied volume) occurred on the Control site compared with 18.1 % of applied water lost to deep drainage in the Treatment site (Figure 6).

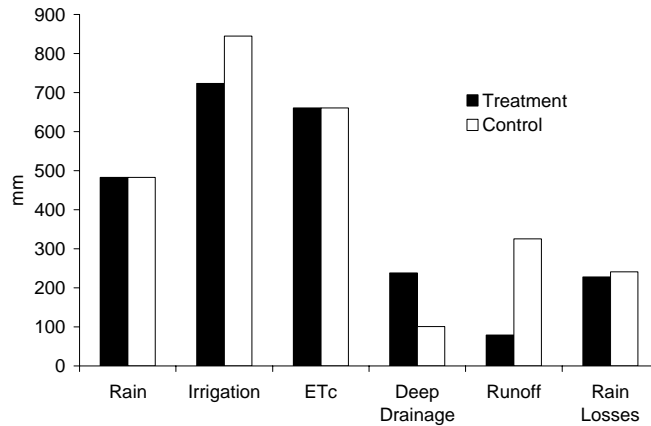


Figure 4. Water balance for the 2004-05 cotton season showing calculated crop evapotranspiration and losses from irrigation events and rainfall

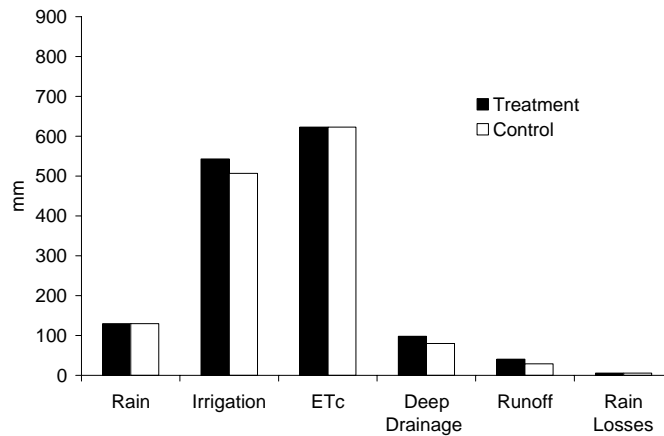


Figure 5. Water balance for the 2005-06 cotton season showing calculated crop evapotranspiration and losses from irrigation events and rainfall

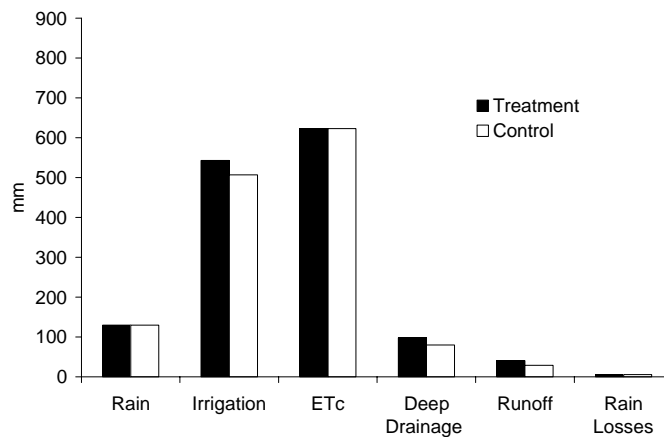


Figure 6. Water balance for the 2006-07 cotton season showing calculated crop evapotranspiration and losses from irrigation events and rainfall

3.1.3 Cumulative infiltration and opportunity time

Soil infiltration characteristics change during the irrigation season due to the effects of soil cultivation and consolidation of the soil surface structure associated with wetting and drying. Hence, the cumulative infiltration graphs for the three seasons show the average infiltration characteristic for the three irrigations at the beginning of each season and the average infiltration characteristic for the subsequent irrigations during the season.

The infiltration characteristics for the Treatment and Control sites during 2004-05 are shown in Figure 7. The early season applications indicate considerable infiltration over long runtimes and where the faster and larger volumes infiltrated in the Treatment as compared to lower volumes in the Control. The Treatment infiltration characteristics indicate large volumes of water filling the crack volume over a short period with continued high rates of infiltration of the length of the irrigation. By contrast, the Control irrigations had low to medium infiltration rates filling the crack volume and then tapering off toward a steady state infiltration rate later in the irrigation. The lower rates of water application on the Control site tended to close the cracks and reduce the initial infiltration of the soil. Infiltration rates in the final hour of the irrigation (Table 3) show considerable differences between the treatments.

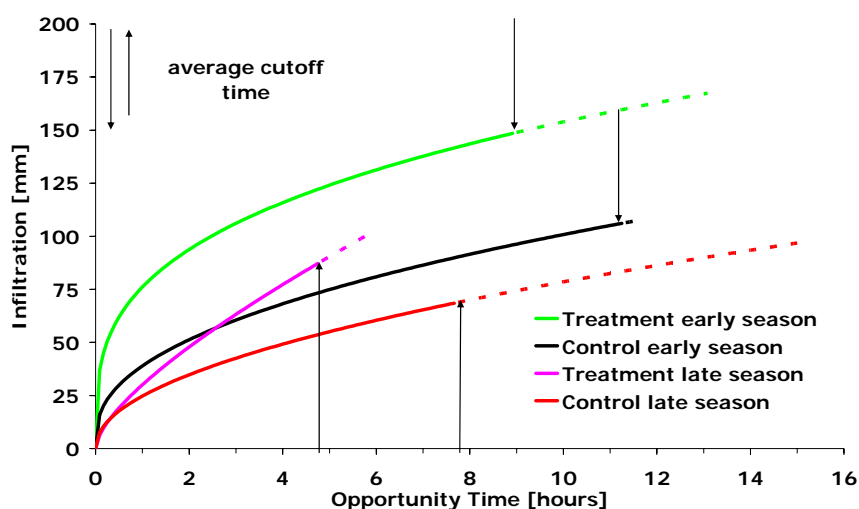


Figure 7. Cumulative infiltration as function of opportunity time for early and late season irrigations for the 2004-05 cotton season. Broken lines indicate maximum opportunity time (maximum cut-off time) and arrows indicate the average irrigation cut-off time for the irrigation groupings.

The shape of the infiltration characteristic at the Control site during the 2005-06 season was demonstrated a high initial infiltration rate (i.e. during crack fill) after which it decreased to a steady 1.7 mm/hr for much of the irrigation event (Figure 8). Hence, even though the Control irrigations were applied for 12.6 hours on average, the total infiltration at the Control site was relatively small (~30 mm/irrigation). By contrast, both the early and late season irrigations at the Treatment site were applied for approximately 4.6 hours on average but there was a higher infiltration rate during the crack fill stage and the final infiltration rate was higher at 4.1 mm/hr (Table 3) resulting in a total infiltration of approximately 50 mm/irrigation. This data and the previous season's data highlights that there is a poor correlation between the period of irrigation and total infiltration.

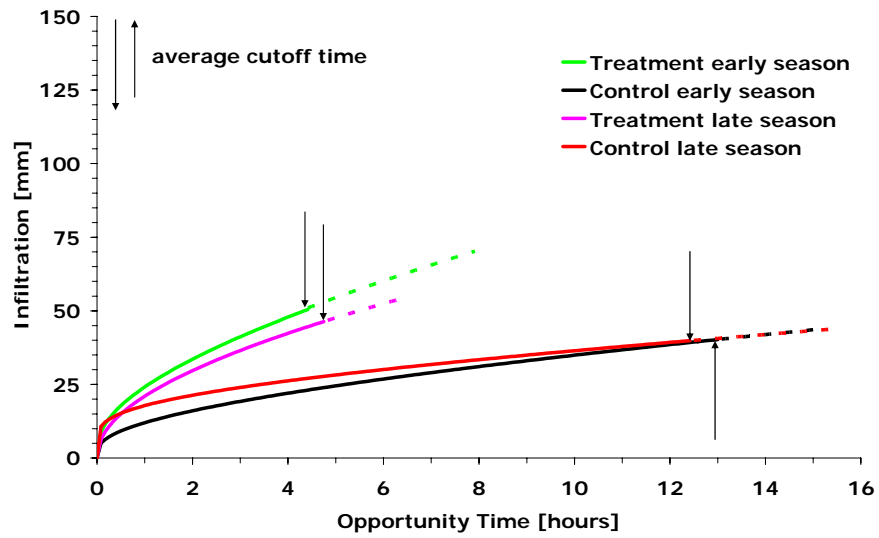


Figure 8. Cumulative infiltration as function of opportunity time for early and late season irrigations for the 2005-06 cotton season. Broken lines indicate maximum opportunity time (maximum cut-off time) and arrows indicate the average irrigation cut-off time for the irrigation groupings.

The 2006-07 season was similar to the 2006-07, in terms of the high infiltration rates observed for the Treatment irrigations and the comparatively low and but reducing infiltration rates at the Control site (Figure 9). Average period of irrigation for the Treatment site was approximately half that of the Control site. The average final infiltration rate at the Treatment and Control sites were 5 and 2 mm/hr, respectively (Table 3).

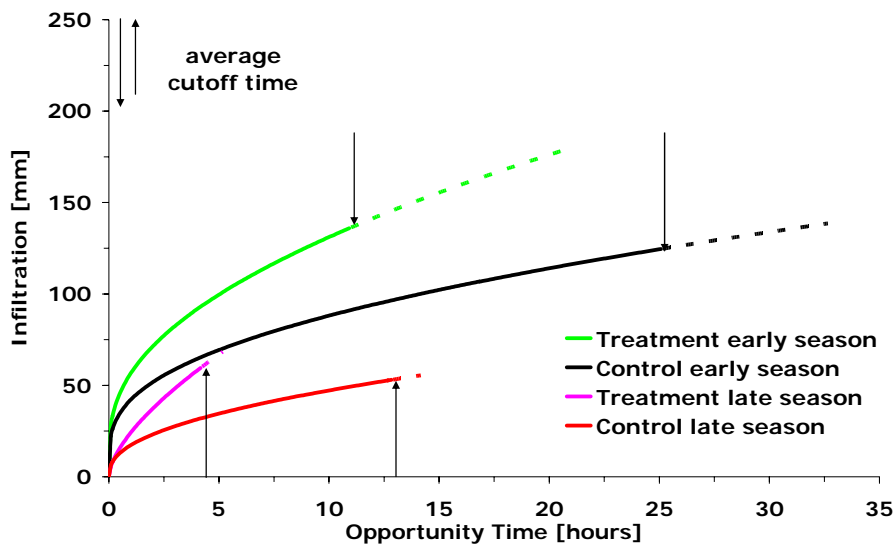


Figure 9. Cumulative infiltration as function of opportunity time for early and late season irrigations for the 2006-07 cotton season. Broken lines indicate maximum opportunity time (maximum cut-off time) and arrows indicate the average irrigation cut-off time for the irrigation groupings.

Table 3. Average infiltration rates during the final hour of irrigation at Lagoon

Season	Irrigation	Treatment (mm/h)	Control (mm/h)
2004-05	Early season	7.0	4.0
	Late season	13.2	6.7
2005-06	Early season	6.5	2.0
	Late season	4.1	1.7
2006-07	Early season	5.0	2.0
	Late season	8.0	2.0

3.1.4 Soil and chemical loss

Water quality data collected throughout the mid and latter parts of the 2004-05 season indicated that the concentration of solids, nitrogen (N), phosphorus (P) and potassium (K) had generally been higher in the Treatment plot tailwater, (Appendix 1, Figure 1a, c, d, b) most probably because of higher furrow flow rates (Table 4). The total export of these contaminants was lower at the Treatment site during the final three 2004-05 irrigations due to the substantially lower volumes of total tailwater. However, the fourth irrigation produced considerable runoff (Table 4 & 5) at both sites and only marginally more offsite movement in the Treatment site (Appendix 1, Figure 1). The concentrations of most other contaminants including Potassium and Prometryn were similar in both the Control and Treatment tailwater, resulting in net export generally being much higher in the Control plot for the late season irrigations. During the last three 2004-05 irrigation events the loss of Prometryn was 0.35 and 0.08 kg/ha, and K was 12.5 and 1.5 kg/ha for the Control and Treatment sites, respectively. Average concentration and net offsite movement of total solids for the last three irrigations were 1533 mg/l and 925 kg/ha for the Control site and 4550 mg/L and 525 kg/ha for the Treatment site.

Water quality analysis from all irrigations events during the 2005-06 season showed similar trends to 2004-05 with the concentration of solids and chemicals in the runoff from the Treatment site higher than that of the Control but the total offsite movement from the Control site being higher than that of the Treatment site (Appendix 1, Figure 2) generally due to the higher flow rates and smaller total runoff volumes. Base loads of total solids, nitrogen and potassium were lower than in 2004-05. Where small quantities of the highly soluble chemical Prometryn was lost offsite during the 2004-05 season, Diuron was lost from the fields during 2005-06 at rates of 18.4 g/ha and 20.5 g/ha for the Treatment and Control sites, respectively.

Time series water quality analysis for early, mid and late season irrigations during 2005-06 are shown in Appendix 1 (Figure 3). Irrigations 1, 6 and 10 for the Treatment site were analysed for turbidity (a), total Nitrogen (e), Potassium (c) and Phosphorous (g). Under the high flow rates applied at the Treatment site, turbidity was initially high (>2000NTU, irrigation 10) during the first hour, but tended to plateau at around 400NTU over the following 3-6 hours of the irrigation events. By contrast, for irrigations 3, 6 and 10 at the Control site, following an initial pulse of moderate turbidity levels of 450-1053NTU, turbidity tended to steadily decline over the 8 hours of the irrigations (Appendix 1, Figure 3b).

Nutrient losses from the Treatment site tended to increase from the first hour of an irrigation event, peaking at over 1 kg/ha for N and K during the third and fourth hours and then tapering off over the 4th to 6th hours of irrigation. The trend was consistent for N, P and K during the pre-season irrigation conducted in October 2005. For subsequent irrigation events, the nutrient losses were not as pronounced, with the exception of P during irrigation 10 (0.09 kg/ha) and to a minor extent during irrigation 6 (0.08 kg/ha) (Appendix 1, Figure 3g). At the Control site, under a much lower irrigation application rate regime (Table 7), the nutrient

losses tended to marginally increase or remain steady with irrigation time. Potassium increased in all irrigations with time, peaking at 0.5 kg/ha during irrigation 10 (Appendix 1, Figure 3d). Phosphorus levels in the tail water tended to remain consistent at 0.01, 0.02 and 0.03 kg/ha during each irrigation respectively (Appendix 1, Figure 3h). Nitrogen losses from the Control site increased marginally during all events peaking at 0.08, 0.06 and 0.18 kg/ha during the 8th hour of each irrigation, respectively (Appendix 1, Figure 3f).

During 2006-07, offsite soil and nutrient movement was principally an issue during the pre-season irrigation events. This major runoff event and the minor ones from the in-crop irrigations generated similar water concentrations for most parameters at both sites. An exception was the Treatment site total solids concentration which was twice that of the Control at 1658 mg/L. The seasonal outflow yielded 460 kg/ha for the Treatment site and 158 kg/ha of total solids for the Control site (Appendix 1, Figure 4a). This was less than half of that generated by the Treatment site outflow during the 2005-06 season at 0.55 ML/ha and 0.41 ML/ha during 2006-07. The decrease in runoff from the Control site (1.13 ML/ha to 0.3ML/ha) contributed to the 90% decrease in offsite movement observed during the 2006/07 season. However, the concentration of nutrients and chemicals in the tail water was marginally increased on the previous season and in most cases the two sites were not as dissimilar as that shown in previous seasons.

Nitrogen and potassium losses during 2006-07 ranged from 2.5-4.4 kg/ha for both sites, while phosphorus losses were distinctly different between the Treatment and Control at 0.4 and 2.4 kg/ha, respectively (Appendix 1, Figure 4d). Although concentrations of Diuron in the tail water were high but similar to previous seasons, the actual offsite movement of the chemical was restricted by the minimal seasonal runoff to 0.6 and 1.0 g/ha for the Treatment and Control sites, respectively, (Appendix 1, Figure 4e).

3.1.5 Irrigation efficiency

The volume of water applied during 2004-05 ranged from 0.6 to 1.7 ML/ha for in-crop irrigations (Tables 4 and 5). It is unlikely that a deficit in excess of 80-90 mm (i.e. 0.8-0.9 ML/ha) would be common in the DVIA, suggesting that there were a number of measured irrigation events where application of water far exceeded the soil moisture deficit.

There generally appeared to be a change in grower management of the Control site throughout the season, due to an increased understanding of the volumes and proportion of water movement within the field. The time to cut-off (TCO) was radically adjusted by the operators for the mid-season irrigations. Historically the irrigations (both whole of farm and the Control site) were 'run' for longer than 10 hours. However, for irrigations 4, 5, 6 and 7 in 2004-05 the TCO was reduced by about half (i.e. 4.3-7.1 hrs) (Table 5). This resulted in a less water being applied and an apparently smaller comparative saving between the Control and Treatment sites than could have been achieved had this "normal" practice not changed. Despite the non-representative change in the irrigation practice at the Control site, analysis indicated that there was 8.4% less water applied to the Treatment site and a large reduction (67.6%) in tailwater runoff.

The first three irrigations of the 2004-05 season were inefficient for both the Treatment (Table 4) and Control (Table 5) sites as inflows vastly exceeded the soil water deficit resulting in considerable losses to runoff and deep drainage (D_{RZ}). Combined losses for the Treatment site during these initial events was 1.18 ML/ha. Although the irrigation requirement (E_R) was met, application efficiency was extremely low at 50% (average) (Table 4). The inflows for the remaining irrigations were a closer match to the required deficit in some instances, but still excessive, causing considerable loss of irrigation water below the root zone (1.75 ML/ha), however with little runoff. With the exception of the fourth irrigation, E_A remained low at

53% for the remainder of the season. Except for the first irrigation average runoff was 7% of applied water for the remainder of the season, a total of 0.69 ML/ha (Total for the season 1.01 ML/ha). Distribution Uniformity (DU) was low for the season, in that there was a 20-25% difference between the averages of the lowest and highest quarters of infiltrated volumes (Table 4) suggesting the inflow rates were not matched to the infiltration characteristics.

Table 4. Irrigation characteristics and SIRMOD performance outputs for the Treatment site, 2004-05

Irrigation	Deficit ML/ha	TCO (hours)	Flow rate (L/sec)	E _a (%)	E _r (%)	DU (%)	Inflow ML/ha	Runoff ML/ha	D _{RZ} ML/ha
1	0.92	13.1	2.3	58.6	99.6	94.4	1.52	0.32	0.29
2	0.45	4.8	4.2	43.7	99.5	76.9	1.02	0.10	0.47
3	0.52	5.3	4.4	56.5	98.5	77.6	0.59	0.00	0.00
4	0.68	3.7	4.3	80.9	94.1	85.9	0.78	0.11	0.00
5	0.72	5.8	3.9	64.3	98.9	73.8	1.11	0.02	0.37
6	0.53	4.2	3.9	65.3	99.6	78.4	0.80	0.05	0.22
7	0.35	3.8	4.1	52.2	99.1	78.5	0.78	0.06	0.38
8	0.39	6.0	4.1	32.4	100.0	72.0	1.20	0.03	0.78

Table 5. Irrigation characteristics and SIRMOD performance outputs for the Control site, 2004-05

Irrigation	Deficit (ML/ha)	TCO (hours)	Flow rate (L/sec)	E _A (%)	E _R (%)	DU (%)	Inflow ML/ha	Runoff ML/ha	D _{RZ} ML/ha
1	0.92	10.9	2.6	54.1	96.8	93.1	1.64	0.54	0.18
2	0.45	11.7	2.7	24.8	99.9	94.4	1.81	0.62	0.74
3	0.57	10.8	2.4	58.8	92.8	94.6	0.90	0.32	0.00
4	0.50	4.3	2.7	73.2	97.1	92.2	0.66	0.26	0.00
5	0.72	5.1	2.5	81.7	82.4	85.7	0.72	0.12	0.00
6	0.71	4.3	2.9	72.3	73.9	91.9	0.72	0.19	0.00
7	0.58	7.1	2.9	89.4	92.4	87.2	0.59	0.05	0.00
8	0.47	15.0	2.9	47.8	99.6	95.4	1.39	1.00	0.00

The irrigation performance at the Control site for the first three and last irrigations of the 2004-05 season typified normal practices for the farm in that, the total inflow for these irrigations was 2-3 times higher than the soil water requirement (Table 5). E_A was extremely low at an average of 46 % for the four irrigations, resulting in 2.5 ML/ha of total runoff for these irrigations. The remaining irrigations (4, 5, 6 and 7) inflows closely matched the deficits and although E_R and DU were lower than the other four irrigations, E_A was higher at 79 % on average but runoff was still substantial at 0.62 ML/ha. Total runoff for the season was 67.6 % higher than the Treatment site at 3.12 ML/ha. Over all irrigations, the DU calculations showed only a 12 % difference between the averages of the lowest and highest quarter of infiltrated volumes. Hence, the inflow rates (<2.9 L/s) were a reasonable match to the infiltration characteristic.

During the 2005-06 season, the irrigation managers reverted to their normal irrigation practices for the Control treatment resulting in an average time to cut-off (TCO) for the Treatment site of 4.6 hours (Table 6) and 12.6 hours for the Control site (Table 7). Seasonal volumes of water were applied to treatment and control sites were 5.38 and 5.25 ML/ha, respectively. DU was similar across all events for both sites, tending to decrease as the season progressed, particularly for the Treatment site where there was an 18 % difference between the averages of the lowest and highest quarter of infiltrated volumes.

Table 6. Irrigation characteristics and SIRMOD performance outputs for the Treatment site, 2005-06

Irrigation	Deficit (ML/ha)	TCO (hours)	Flow rate (L/sec)	E _A (%)	E _R (%)	DU (%)	Inflow (ML/ha)	Runoff (ML/ha)	D _{RZ} (ML/ha)
1	0.50	8.0	2.1	64.0	100.0	88.2	0.80	0.15	0.16
2	0.28	3.0	3.5	58.7	100.0	82.1	0.48	0.04	0.15
3	0.29	3.6	3.4	47.4	102.5	78.7	0.58	0.02	0.27
4	0.60	3.1	4.7	72.5	40.3	94.7	0.33	0.09	0.00
5	0.31	3.9	4.4	67.2	99.3	88.1	0.43	0.07	0.04
6	0.35	5.0	4.1	71.4	98.4	75.2	0.48	0.02	0.11
7	0.37	6.5	4.1	58.5	100.0	89.8	0.63	0.11	0.14
8	0.27	3.6	4.2	74.5	98.6	79.0	0.36	0.02	0.08
9	0.33	4.7	4.3	69.6	99.2	76.0	0.46	0.01	0.12
10	0.26	3.8	4.0	73.7	98.5	75.1	0.35	0.00	0.09
11	0.21	5.8	3.6	43.8	99.7	70.6	0.47	0.01	0.25

Table 7. Irrigation characteristics and SIRMOD performance outputs for the Control site, 2005-06

Irrigation	Deficit (ML/ha)	TCO (hours)	Flow rate (L/sec)	E _A (%)	E _R (%)	DU (%)	Inflow (ML/ha)	Runoff (ML/ha)	D _{RZ} (ML/ha)
1	0.40	12.8	1.7	73.3	95.8	93.0	0.52	0.11	0.01
2	0.28	15.0	1.3	56.0	100.0	89.9	0.50	0.10	0.12
3	0.29	10.4	1.6	70.5	99.4	80.8	0.41	0.04	0.08
4	0.60	13.8	1.7	69.3	65.7	92.9	0.57	0.17	0.00
5	0.25	13.6	1.7	44.6	100.0	95.9	0.56	0.25	0.06
6	0.40	10.5	1.5	91.1	89.9	78.2	0.39	0.02	0.00
7	0.40	11.8	1.7	71.9	94.8	87.8	0.50	0.10	0.00
8	0.40	15.5	1.5	64.0	100.0	87.7	0.58	0.09	0.10
9	0.33	11.4	1.5	67.8	87.1	93.2	0.42	0.13	0.00
10	0.35	12.5	1.2	76.2	80.8	89.6	0.37	0.08	0.00
11	0.21	11.4	1.4	49.8	100.0	85.2	0.42	0.02	0.19

Inflow rates at the Treatment site ranged from 2.1 to 4.7 L/s (Table 6) which tended to produce higher DUs during the early season (i.e. Irrigations 1-5). However, the average inflow of 4 L/s over the remainder of the season produced lower DUs which would be considered marginal by industry standards. The difference between average infiltrated volume field quartiles in the Control was 13%. The low inflow rates resulted in long opportunity times even at the end of the season, as reflected by 19 mm of deep drainage in

irrigation 11 (Table 7). The Control site E_R was considerably lower than that of the Treatment site as the deficit was not met for six of the 11 irrigation events (Table 7), but exceeded by infiltrated volume for the Treatment (Figure 2b). Irrigation 4 on the Treatment site was the only event that failed to meet the soil water requirement (Table 6). The poorly matched large application volumes to the low soil moisture deficit at the Treatment site resulted in considerable seasonal loss of irrigation water (1.41 ML/ha) to drainage below the root zone (D_{RZ}) (Table 6). However runoff was restricted to <5% of average irrigation inflows for most events and total seasonal runoff was 0.55 ML/ha. At the Control site, inflow substantially exceeded the soil requirement, which resulted in considerable losses to runoff (1.13 ML/ha) which were 49 % higher than the losses from the Treatment site (Table 7). With the exception of irrigations 3, 6, and 11, runoff from the remainder of the irrigation events averaged 26 % of inflows (range 21- 45%). Losses for the three isolated events were 10, 6, and 4 % of inflows, respectively. D_{RZ} was 61% less than the Treatment site, but total losses on both sites resulted in equally poor application efficiencies at 63.4% (Treatment) and 66.8% (Control) for the season.

In the final season the applied volumes were also poorly matched to the soil deficit which resulted in over irrigation during the early season and under irrigation for the remainder, mostly due to the lack of irrigation water (Tables 8 and 9). With the exception of the first wetting up irrigation in both Control and Treatment, runoff generated from the latter was half that of the Control site on average at 0.02 ML/ha, which was 2% of inflow, compared with 5% of inflow for the Control site. Application efficiency was variable in the first three irrigations ranging from 51-78% at both sites, which resulted in considerable runoff and deep drainage. At the Treatment site, excessive TCO at low flow rates (1.9 L/s) in each furrow, resulted in 0.32 ML/ha in runoff and 0.30 ML/ha in deep drainage during the wet up irrigation (Table 8). The second irrigation using high flow rates (6.0 L/s) in alternate furrows generated 0.5 ML/ha (45.5% of inflow) deep drainage as a result of longer than required TCO (8 hours). The DU in irrigations 2-6 changed considerably with larger inflow rates. However, in the final irrigations with slightly lower inflows (5.3 L/s) DU improved marginally. By contrast, as in earlier seasons, the Control site lower flow rates tended to produce DU at or above 75% for the season.

Losses from the Control site during the first irrigation were considerably lower with only 7.7 and 13.8 % of inflow lost to runoff and deep drainage respectively (Table 9). As the season progressed, TCO was reduced and consequently runoff was maintained on average at 5.4 % of inflow. Deep drainage was reduced to near zero at the Control site, raising application efficiency, but reducing E_R in the latter irrigations of the season (Table 9). The second irrigation, as at the Treatment site, was excessive with deep drainage at 42.5% of inflow. Because inflow exceeded the deficit by a considerable margin, E_A was reduced to 53.5 %. Overall, E_R declined as the season progressed with ever diminishing water resources and where total irrigation inflows were unable to satisfy the soil water requirements.

Table 8. Irrigation characteristics and SIRMOD performance outputs for the treatment site, 2006-07

Irrigation	Deficit (ML/ha)	TCO (hours)	Flow rate (L/sec)	E_A (%)	E_R (%)	DU (%)	Inflow (ML/ha)	Runoff (ML/ha)	D_{RZ} (ML/ha)
1	1.20	20.8	1.9	67.0	100.0	88.7	1.82	0.32	0.30
2	0.57	7.9	6.0	51.6	99.2	74.9	1.10	0.03	0.50
3	0.54	5.8	5.8	69.2	95.8	62.5	0.75	0.03	0.18
4	0.63	5.3	5.5				0.60	0.00	0.00
5	0.76	3.8	5.3	94.8	56.9	77.3	0.46	0.02	0.00
6	0.93	5.3	5.3	99.3	72.4	67.2	0.70	0.01	0.00

Table 9. Irrigation characteristics and SIRMOD performance outputs for the control site, 2006-07

Irrigation	Deficit (ML/ha)	TCO (hours)	Flow rate (L/sec)	E _A (%)	E _R (%)	DU (%)	Inflow (ML/ha)	Runoff (ML/ha)	D _{RZ} (ML/ha)
1	1.20	32.8	2.0	78.3	100.0	82.3	1.52	0.12	0.21
2	0.57	23.4	2.0	53.5	99.7	75.2	1.06	0.05	0.45
3	0.59	19.3	1.8	73.0	98.0	74.8	0.78	0.04	0.14
4	0.63	12.0	2.2				0.61	0.00	0.00
5	0.71	12.5	1.8	92.3	65.9	76.9	0.50	0.04	0.00
6	0.84	14.1	1.8	90.7	64.5	79.8	0.60	0.05	0.00

3.1.6 Yield and Cotton Quality

Cotton yield was higher at the Treatment site during 2004-05 compared to the grower managed Control site by 1.36 bales/ha (Table 11). The reduced yield in the Control site was due to excessive vegetative growth at the head ditch end of the Control site e.g. crop height was 130 cm in the control compared with 122 cm for the treatment (complete data set was not available). The number of fruiting branches was also considerably reduced in the Control site (14.8) compared to the head ditch end of the Treatment site (17.8) complete data set was not available). The total number of bolls in the head ditch end of both sites were similar at 122 per m. However, at the tail drain end, the number of bolls were 112 and 100 per m for the Control and Treatment, respectively (complete data set of seasonal plant mapping was not available). Volumetrically, the largest difference between the sites was the total volume of runoff which caused considerable differences in irrigation water use index (IWUI) which was 0.81 and 1.05 bales/ML for the Control and Treatment sites, respectively. The effective gross production water use index (GPWUI) was low at 0.51 and 0.65 bales/ML for the Control and Treatment sites, respectively (Table 11).

Table 10. The 2004-05 cotton season water use efficiency at field scale and yield for the Control and Treatment sites.

Site Data	Control	Treatment
Area (ha)	2.5794	2.88
Slope	0.0021	0.0016
Slope Range	0.0006 – 0.0032	0.0002 – 0.0032
Yield (b/ha)	6.79	8.15
Irrigation Averages		
Average Flow Rate per Furrow (l/s)	2.71	4.12
Average Time to Cutoff (hours)	8.70	5.85
Average Volume Applied (ML/ha)	1.05	0.89
Minimum volume applied (ML/ha)	0.60	0.50
Maximum volume applied (ML/ha)	1.81	1.20
Average volume tailwater (ML/ha)	0.16	0.03
Season Totals		
Total volume applied (ML/ha)	8.41	7.73
Total volume tailwater (ML/ha)	3.25	0.79
Total rain (mm)	485.20	484.50
Effective rain (mm)	482.50	482.50
Water Use Indices		
IWUI (b/ML)	0.81	1.05
GPWUI (total)(applied) (b/ML)	0.51	0.65
GPWUI (effective)(applied) (b/ML)	0.51	0.65

The difference in yield between the sites for the 2005-06 season was less than 0.8 bales/ha. However, there was no obvious difference in the IWUI (Table 12) with 2.10 and 2.11 bales/ML for the Control and Treatment, respectively. Effective GPWUI was three times the value of the previous season at ~1.50 bales/ML (Table 12). Irrigation characteristics were similar in terms of volume applied, but flow rates and TCO were quite dissimilar as described previously and shown in Table 12. Total runoff in the Control was twice that of the Treatment at 1.13 ML/ha (Table 12).

The difference in yield between the head and tail drain ends of the field was variable in the Control site and less so in the Treatment (Figure 10a). Where the Treatment site yield difference between the mid and tail drain sections of the field was 0.3 bales/ha, in the Control site this difference was much larger at 1.9 bales/ha. This comparative trend between the field ends and the mid section continued for the head ditch end of both sites. However, the differences between head and mid field sections were considerably larger in the Control than the Treatment sites at 2.6 and 2 bales/ha, respectively.

Table 11. The 2005-06 cotton season water use efficiency at field scale and yield for the Control and Treatment sites.

Site Data	Control	Treatment
Area (ha)	3.0803	4.0184
Slope	0.0021	0.0016
Slope Range	0.0006 – 0.0032	0.0002 – 0.0032
Yield (b/ha)	10.52	11.30
Irrigation Averages		
Average Flow Rate per Furrow (l/s)	1.54	4.04
Average Time to Cutoff (hours)	12.60	4.53
Average Volume Applied (ML/ha)	0.48	0.51
Minimum volume applied (ML/ha)	0.36	0.34
Maximum volume applied (ML/ha)	0.56	0.63
Average volume tailwater (ML/ha)	0.04	0.02
Season Totals		
Total volume applied (ML/ha)	5.01	5.35
Total volume tailwater (ML/ha)	1.13	0.55
Total rain (mm)	220.00	220.00
Effective rain (mm)	181.00	181.00
Water Use Indices		
IWUI (b/ML)	2.10	2.11
GPWUI (total)(applied) (b/ML)	1.46	1.50
GPWUI (effective)(applied) (b/ML)	1.54	1.58

The water use efficiency indices in 2006-07 were lower compared to the previous years due to the low crop yield. Low yield resulted from reduced water availability for irrigations during the latter half of the season and low in-crop rainfall. Although the volume of irrigation water applied was similar to that of the previous year (Tables 12 and 13) the individual irrigation application volumes and corresponding deficits were distinctly different (Figures 2 and 3). The over irrigation in the first three events reduced available water for later in the season thus crop water requirements could not be met. Effective GPWUI was equivalent for both sites at approximately 1.42 bales/ML (Table 13). Although overall yield was similar for both sites the infield variability was distinctly different in that the Treatment site had a more consistent crop from top to bottom of the field (Figure 10b).

Table 12. The 2006-07 cotton season water use efficiency at field scale and yield for Control and Treatment sites.

Site Data	Control	Treatment
Area (ha)	6.28	6.28
Slope	0.0021	0.0016
Slope Range	0.0006 – 0.0032	0.0002 – 0.0032
Yield (b/ha)	7.67	7.41
Irrigation Averages		
Average Flow Rate per Furrow (l/s)	1.91	5.57
Average Time to Cutoff (hours)	16.25	5.27
Average Volume Applied (ML/ha)	0.85	0.72
Minimum volume applied (ML/ha)	0.50	0.46
Maximum volume applied (ML/ha)	1.53	1.10
Average volume tailwater (ML/ha)	0.05	0.07
Season Totals		
Total volume applied (ML/ha)	5.07	5.43
Total volume tailwater (ML/ha)	0.29	0.41
Total rain (mm)	175.00	175.00
Effective rain (mm)	130.00	130.00
Water Use Indices		
IWUI (b/ML)	1.51	1.37
GPWUI (total)(applied) (b/ML)	1.12	1.03
GPWUI (effective)(applied) (b/ML)	1.20	1.10

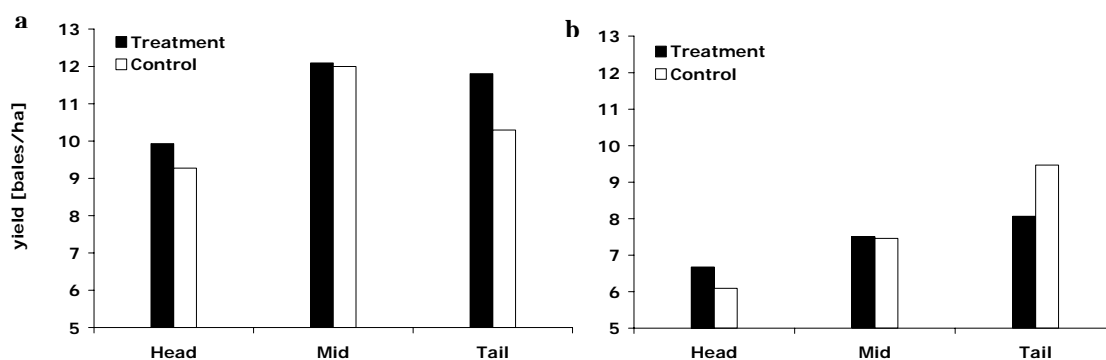


Figure 10. Cotton yield in the head, middle and tail sections of the treatment and control fields for the (a) 2005-06 and (b) 2006-07 cotton seasons.

Cotton quality was only measured in the second and third seasons (Figures 11 and 12). Generally there was less variability along the field in quality parameters within the Treatment compared to the Control site for the 2005-06 season. Length, short fibre index, elongation and micronaire exhibited less variability (Figure 11a, c, e, and f). The Treatment site uniformity and strength (Figure 11b & d) were also considerably improved compared to Control but they appeared to be just as variable along the length of the field. Length, strength and uniformity in the Control site were lower for the head ditch end of the field (Figure 11a, b & d). In terms of discounted price for the cotton, the Control site would have incurred discounts for length, strength and uniformity. Both sites would have incurred discounts for high micronaire and poor elongation.

Variability differences in cotton quality over the length of the field in 2006-07 was not as apparent as in 2005-06. Length, strength and uniformity in the Treatment site were improved compared to the Control site (Figure 12a, b, & d). However, elongation and micronaire were similar between sites (Figure 12e & f) with improved SFI in the Control site.

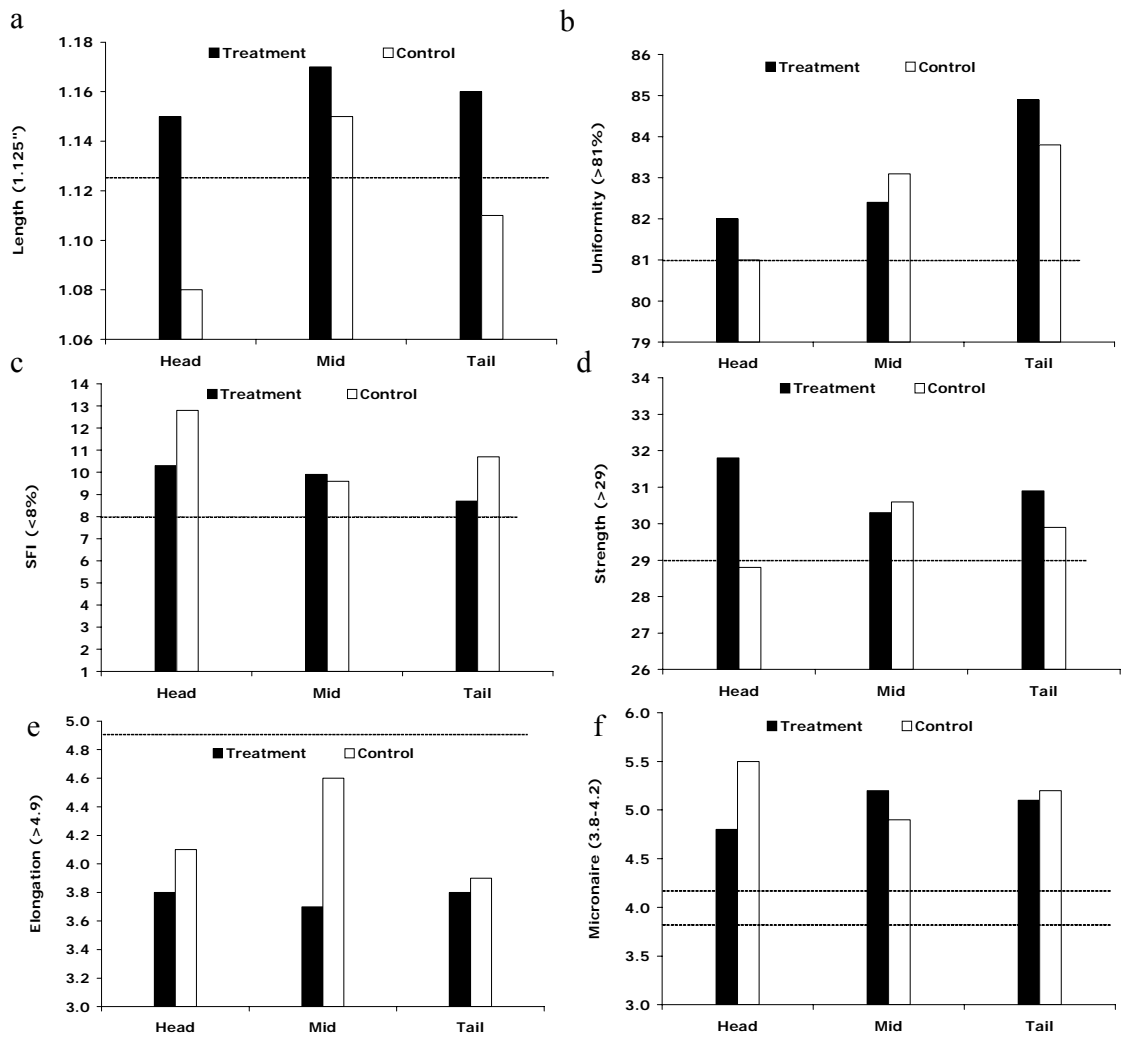


Figure 11. Cotton quality parameters; length (a), uniformity (b), short fibre index (c), strength, elongation (e) and micronaire (f), from the field sections of head ditch end, mid field and tail drain of the control and treatment fields during the 2005-06 season.

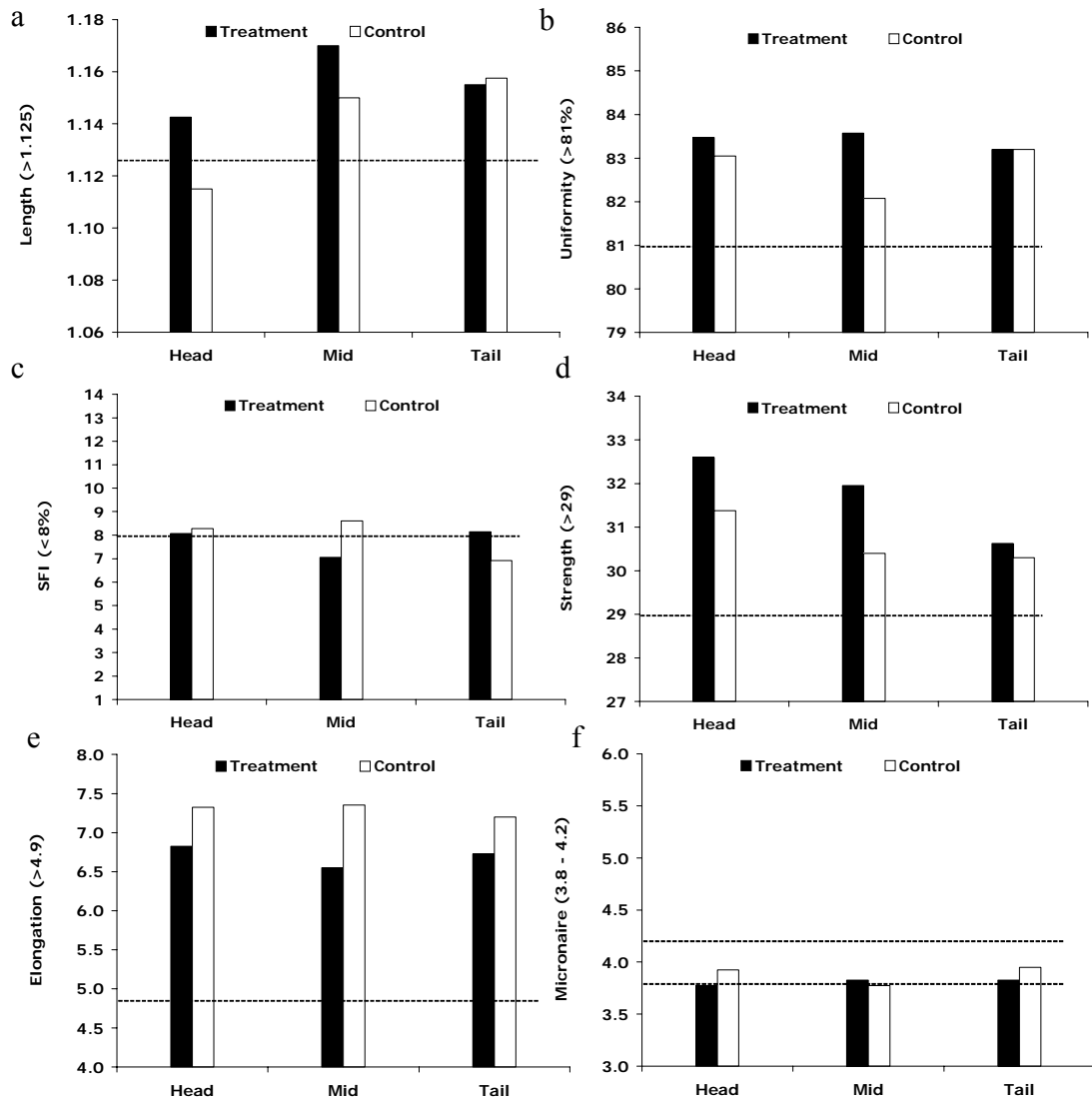


Figure 12. Cotton quality parameters; length (a), uniformity (b), short fibre index (c), strength, elongation (e) and micronaire (f), from the field sections of head ditch end, mid field and tail drain of the control and treatment fields during the 2006-07 season

3.2 Regional analysis of infield crop variation due to irrigation and field optimisation trials

Numerous farms in the DVIA were found to have variable infield crop vigour as indicated in the colour variation from red (good crop vigour) to blue in the processed NDVI images (Figure 13). In some instances, vigour appeared to be related to field position (i.e. differences between the head and tail drain ends of the fields). However, a causal relationship between irrigation performance and NDVI could not be inferred from the data available.

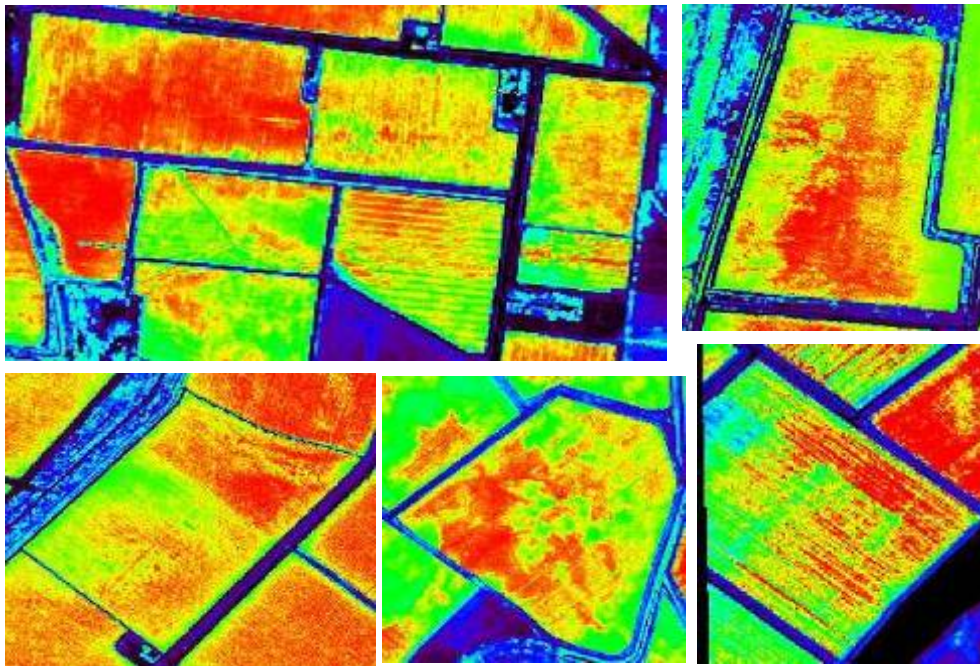


Figure 13. Selected NDVI images of cotton fields under cropping located in the DVIA, 2003-2004

Five farms in the DVIA were found to have similar irrigation management strategies to the Control site at Lagoon (Table 7) in terms of TCO and marginally higher siphon flow rates (Table 13a). Water balance calculations for five irrigations on these individual farms in the DVIA suggested that the volume of irrigation water applied was considerably greater than the soil water deficit (Figure 14a). The deficits used in the water balance calculations ranged from 0.7 to 0.8 ML/ha, which was considered high for the region and considerably higher than those calculated for the Lagoon site. However, the irrigation volume applied ranged from 0.99 to 1.27 ML/ha. Generally large deficits result on long irrigations, but are generally suited to medium flow rates. In all of these cases, the longer than warranted irrigations caused significant volumes of inflow to be lost to deep drainage and runoff (Figure 14a). Optimisation of the irrigation events by reducing the TCO considerably reduced losses (Figure 14b). Application efficiencies for the five farms ranged from 47.3 to 75.2% before optimisation (Table 13a) as a direct result of the long irrigation 'run times' and medium flow rates, leading to the runoff and deep drainage losses. For example D_{RZ} for farm 1 was 29.5% of inflow while runoff for farm 5 was 43.3% of irrigation inflow. The majority of these farms had approximately 10 irrigations each, which could constitute a loss of approximately 5.5 ML/ha on farm 5 and substantial losses on the others as well.

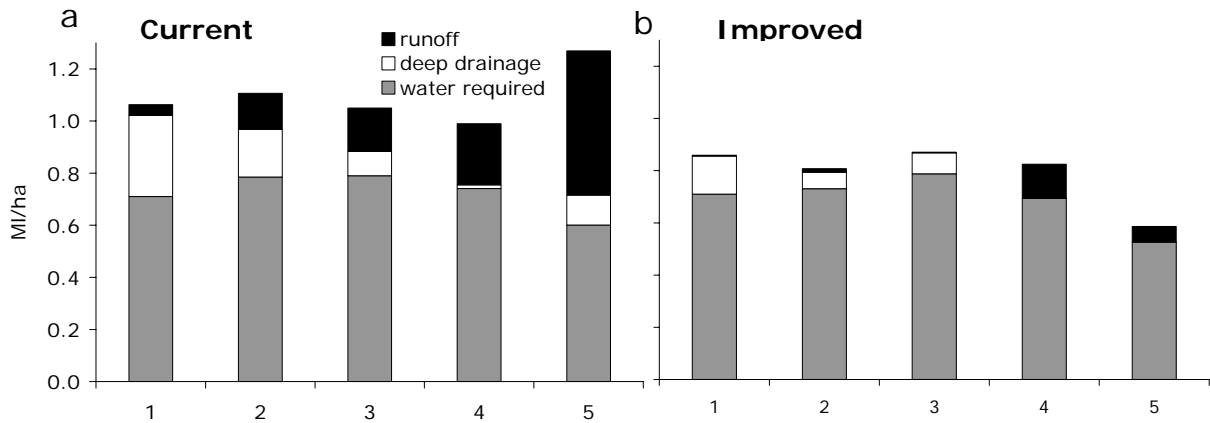


Figure 14. Simplified water balance for five farms in the DVIA describing measured conditions in 2005-06 season and improved/modified irrigation practice after optimisation

Table 13. Inflow, time to cut-off off and irrigation performance for the (a) measured “extra” irrigation events in the DVIA and the (b) changes imposed on inflow, time to cut-off , and resultant efficiencies after optimisation

a Current									
Irrigation	Deficit ML/ha	TCO (hours)	Flow rate (L/sec)	E_a (%)	E_r (%)	DU (%)	Inflow ML/ha	Runoff ML/ha	D_{RZ} ML/ha
1	0.70	9.7	4.5	66.5	100.0	79.6	1.05	0.04	0.31
2	0.79	12.3	3.0	71.1	99.6	83.6	1.11	0.14	0.18
3	0.80	13.8	2.5	75.2	100.0	97.7	1.05	0.17	0.09
4	0.77	10.6	2.8	74.8	96.0	89.9	0.99	0.23	0.01
5	0.60	12.3	4.2	47.3	100.0	93.3	1.27	0.55	0.12
b									
Improved									
1	0.70	6.4	6.2	82.4	98.2	78.9	0.85	0.00	0.15
2	0.79	8.9	3.0	90.5	92.2	71.6	0.81	0.01	0.06
3	0.80	11.5	2.5	90.5	100.0	96.0	0.87	0.00	0.08
4	0.77	8.8	2.8	84.2	90.3	87.7	0.83	0.13	0.00
5	0.60	5.7	4.2	89.9	87.9	91.2	0.59	0.06	0.00

As with the similar irrigations at Lagoon the deficits were exceeded by large margins and thus the E_R values were at or near 100 %. An average DU of 87 % indicates a 13 % difference between the averages of the lowest and highest quarter of infiltrated volumes. A DU of 79.6 % at Farm 1 was inferior at a 20.4 % difference between the lowest and highest quarters of infiltrated volume (Table 13a).

Table 13b describes the irrigation characteristics and performance after a change in average irrigation runtime of 3.5 hours. TCO was reduced by 6.6 hours on farm 5 and lesser amounts on the others, resulting in substantially reducing or removing runoff and deep drainage similar to that experienced in year one at Lagoon. In one instance flow rate was increased by 1.7L/s on farm 1 to achieve optimum results. Flow rates were generally unchanged under improved management and hence, resultant DUs were also largely unchanged. E_A was improved to well above industry standards and with runoff recycling, were possible, E_A could be higher still.

3.3 Case studies

3.3.1 Increasing the capacity of Agronomic Cotton Consultants in the Theodore Region to Assist in Improved Water Use Efficiency of their Clients.

Irrimate™ irrigation evaluations provide furrow irrigators with information about the uniformity and efficiency of their irrigation applications. Under the Irrimate™ agreement certified level 1 consultants can analyse the data and provide feedback to the client. In order to be compliant to this model the “project” sent the irrigation data to Sustainable Irrigation Systems (A registered level 1 Irrimate™ service provider) in order to analyse the data and provide the results to the agronomist and their client. Data was provided and analysed and the results were sent for a number of irrigations and then discussions were made about the data and feedback was provided in relation to the content and format of reporting. This generated a discussion resulting in:

- (a) The consultant demonstrated a high level of awareness of the type of data being provided, and
- (b) The consultant provided strategic feedback about how the data should be presented to themselves and ultimately their clients.

The consultant demonstrated a high level of awareness about the data as indicated by the level of questioning. The following points were made:

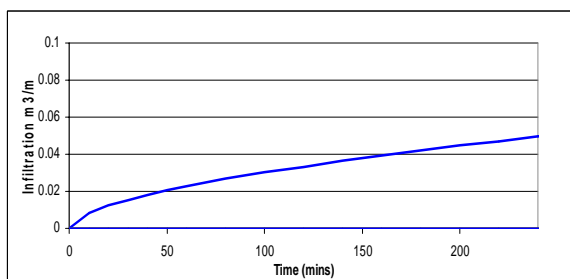
- (a) The first thing that a consultant and grower would look at is infiltration as compared to deficit. So this must stand out or be bolded. A discussion was raised about deficits and it was agreed that this needs further attention as it is the part that the whole report hinges upon.
- (b) Growers just want to know how good or bad they are and what they should be aiming for. The consultant felt that targets for the various efficiencies should be provided for this reason.
- (c) Strategies for improvement, where necessary, should be provided and must be practical. Therefore there is a need for discussion between agronomist and client to focus on the possibilities so that improvement scenarios make sense.
- (d) The infiltration curve is a very important tool when discussing the results and the reasons for the measured efficiencies. They are also important for discussions about why stopping siphons early is important and whether a system change may be necessary. For simplicity data should be provided in ML/ha.

3.3.2 On Farm Irrigation Assessments – A Case Study “Acacia”

On Farm Irrigation Assessments evaluate how accurately and uniformly water was applied during an irrigation event. Accuracy implies a target. The target is the DEFICIT. On Farm Irrigation Assessments provide four things:

- 1) Infiltration Characteristic of the soil – How leaky is your soil?
- 2) Application Efficiency (AE) – % of water delivered to the paddock that is used to refill the deficit.
- 3) Distribution Uniformity (DU) – How evenly is the water applied from head ditch to tail drain.
- 4) Optimisation – Using a computer model to develop Irrigation Best Practice.

An on farm irrigation assessment was conducted by Simon Strauss on the 5th irrigation of Field 4, Acacia during the 2005-06 season.



Infiltration Characteristic

Usually represented as a graph it shows the amount of water entering the soil per unit time. Typically most of the deficit is refilled quickly (at least within first hour) and then the infiltration slows to a final steady rate anywhere between <1 mm/hr and 6 mm/hr.

The final infiltration rate at Acacia (graph is not flattening out) was high at 5 mm/hr. This

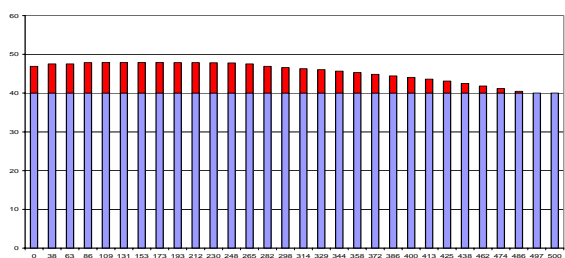
means that siphons run well in excess of average advance which could generate water losses of up to 0.05ML/ha/hr. As it turned out the siphons were stopped within 1 hour of the average advance to the end of the paddock.

Application Efficiency

Deficit	40 mm
Applied	62 mm
Runoff	16 mm
Infiltration	46mm

The deficit was 40 mm and 62 mm was delivered to the paddock through the siphon. By definition that means AE = 65%. That is 65 % of the water that was delivered to the paddock was used to refill the deficit. But

not all tail-water is lost. So unless reticulation losses are measured then it is assumed that 85% of tail-water can be reused. This adjustment increases AE to 86 %. The losses are drainage beyond the root zone or in excess of deficit (6 mm or 10%) and losses due to seepage and evaporation while tail-water is being recycled (4 mm or 4%). Improvements in AE result in less deep drainage and a reduction in the losses and costs associated with the reticulation of water.



Distribution Uniformity

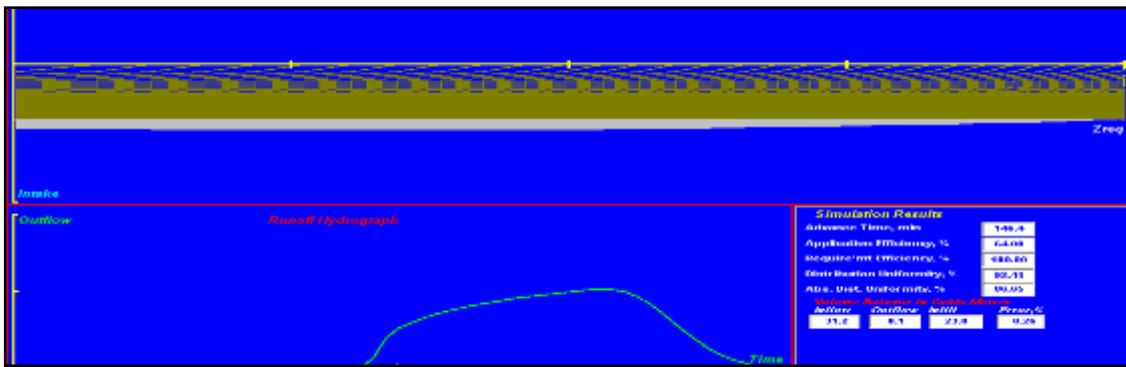
The DU at Acacia was high at 92 % which means there is an 8 % difference between the averages of the lowest and highest quarter of infiltrated volumes. Improvements in uniformity generally mean that the water has to get to the end of the paddock quicker and then switched off to minimise the opportunity time for drainage in the head ditch area, particularly

on leakier soils. Improvements in DU result in more even crops and the associated benefits including fertiliser efficiency.

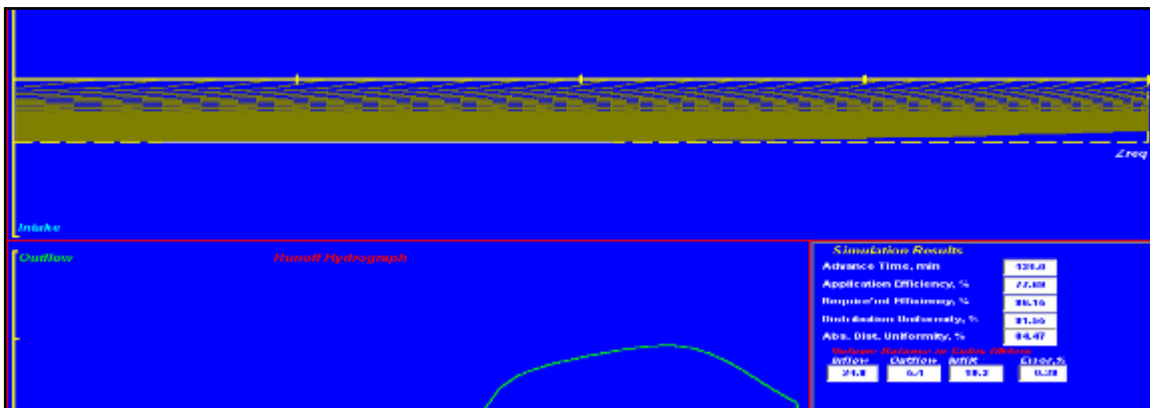
Optimisation

The parameters collected during the on farm irrigation assessment are entered into the Surface Irrigation Model (SIRMOD). The siphon flow rate, cut off time, deficit, furrow length and slope can be manipulated to improve performance.

A SIRMOD output showing a cross sectional view of the irrigation as measured during the irrigation event.

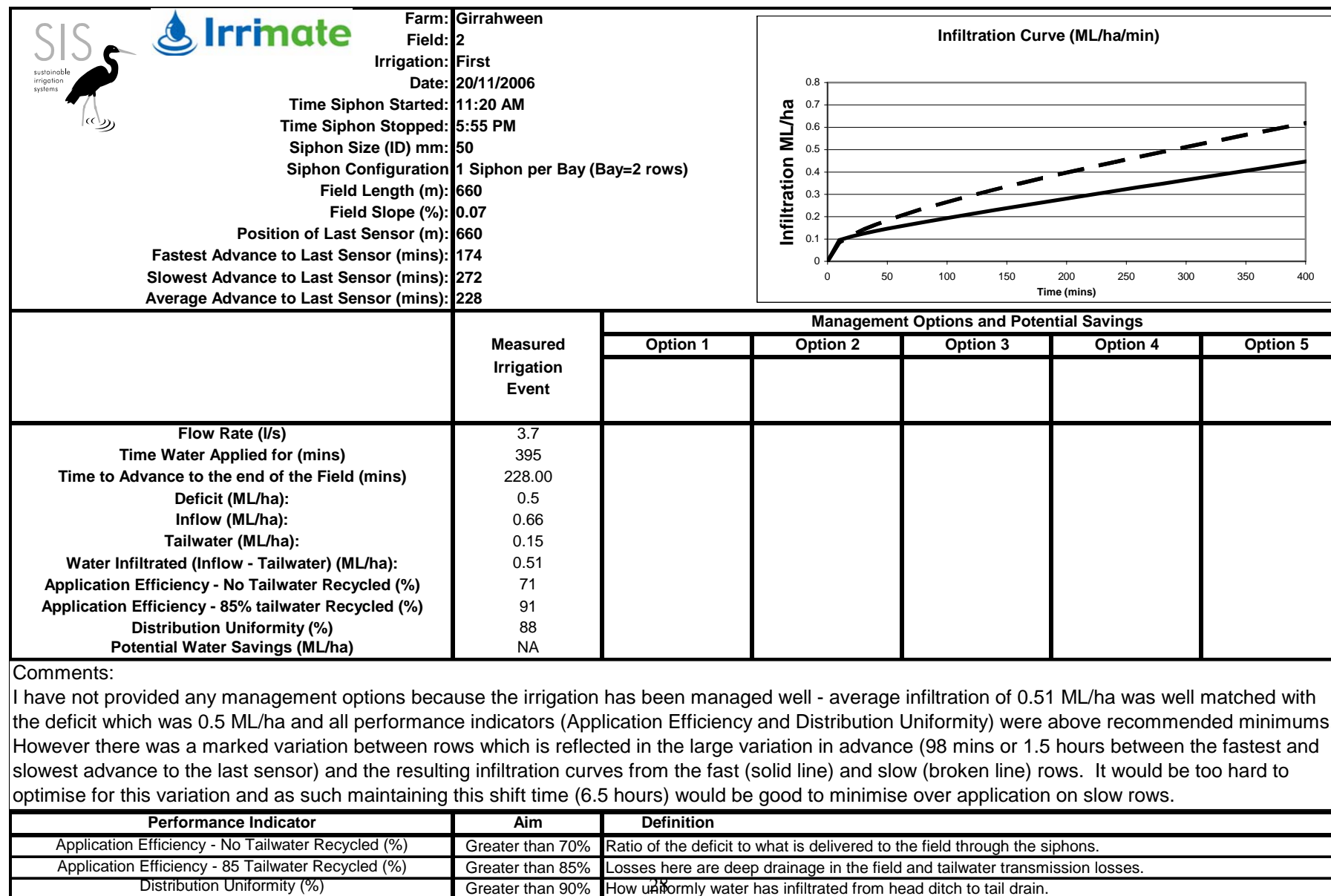


Uniformity is maintained by increasing the flow rate slightly while mitigating the opportunity time for drainage in the head ditch area. Also by stopping the siphons an hour earlier AE is increased to 96 %.



NOTE – On farm irrigation assessments provide information relevant to: Worksheet 9 -Maximise Application Efficiency, Worksheet 10 - Monitor Water Use and Calculate Efficiencies and Worksheet 11 - Aim for Uniform Application, of the Cotton BMP Land and Water Management Module.

3.3.3 On Farm Irrigation Assessments – A Case Study “Girrahween”



3.3.4 On Farm Irrigation Assessments – A Case Study “Lagoona”

Introduction

A field trial was conducted in an attempt to quantify the whole field irrigation performance. The resulting experimental data from Lagoona provided an opportunity to demonstrate the application of the techniques developed at USQ. Detailed advance and runoff measurements from a small number of furrows enabled the use of the IPARM model to estimate the infiltration curves. The procedure was used to predict the infiltration parameters based on completion times for a large number of additional furrows. The collection of furrows is used to demonstrate the use of the whole field simulation and optimisation model.

Field Data

The Lagoona data was collected from a furrow irrigated field planted to cotton, south of Theodore in the Dawson River valley in central Queensland (Figure 15). All measurements were collected during the second irrigation (first in crop irrigation) of the 2006-07 season. Field inflow was measured using a STARFLOW Doppler meter mounted within the inlet pipe upstream of the supply head ditch, logging velocity and area of flow at five minute intervals. The resulting hydrograph did not exhibit any significant temporal changes therefore the inflow was assumed to be constant over time. This was further confirmed by an Irrimate™ siphon flow meter installed in one of the furrows. A number of siphon head measurements were also collected and the discharge was estimated using the procedure explained by Bos (1989). The resulting inflow rates were found to be in close agreement with the discharge measured using the STARFLOW meter.



Figure 15. Advance meter 0 m (head-ditch) in Lagoona trial

Figure 16 depicts the layout of the trial field showing the relative positions of advance sensors and runoff flumes. Normal advance data was collected at four or five positions along the furrow length for eight wetted furrows, limited measurements were also collected for an additional 76 furrows. The furrows with detailed advance measurement were situated close to but not adjacent to the edge of the field (on both sides of the field). The time taken to reach the final advance distance of 761 m was measured for all 84 wetted furrows. In, addition the time taken to reach the midpoint (460 m) was measured for 20 furrows located approximately in the middle of the field (Figure 16). Flumes to measure runoff were positioned in wetted furrows numbers 5, 39 and 67. Runoff discharges were recorded in 5 minute intervals for these furrows. Due to difficulties with furrow breakthrough, the flow of one of the adjacent “unwetted” furrows was directed across into the wetted furrow upstream of the flume.

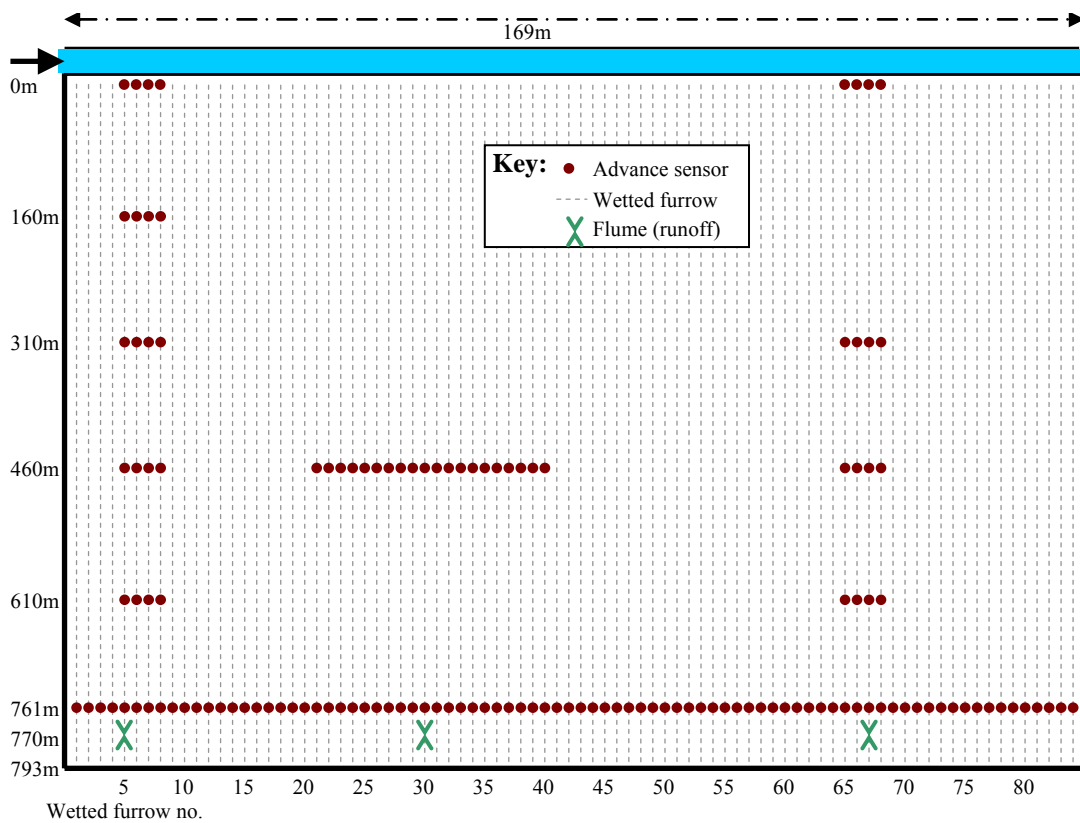


Figure 16 Lagoona field trial layout

Initial observation of the advance completion times (Figure 17) indicated that the furrows with detailed measurement experienced advance rates that were representative of the remainder of the field. The variation of advance times does not appear entirely random. The wetted furrows numbered 15-50 tend to have slower advance rates than the other furrows. This effect may be caused by decreased inflow rates as the result of changing siphon head or differences in soil characteristics resulting from laser levelling. Part of the variation between closely spaced furrows is caused by compaction by machinery operations. Field observation indicated that every second wetted furrow is compacted with furrow number one being compacted (i.e. furrows 1, 3, 5 etc are compacted). The compacted furrows have increased advance rates at a significance level of 0.01 assuming independent sampling. Considering the difference between adjacent furrows (paired t test), the compacted furrows have increased advance rates at a 0.05 level of significance. Furthermore, the increase in advance time between adjacent furrows due to compaction was found to be 36.5 and 47.3 minutes ($\alpha=0.05$) moving forward (i.e. furrow 1 vs. 2, 3 vs. 4,...) and backwards (furrows 2 vs. 3, 4 vs. 5,...) across the furrows, respectively.

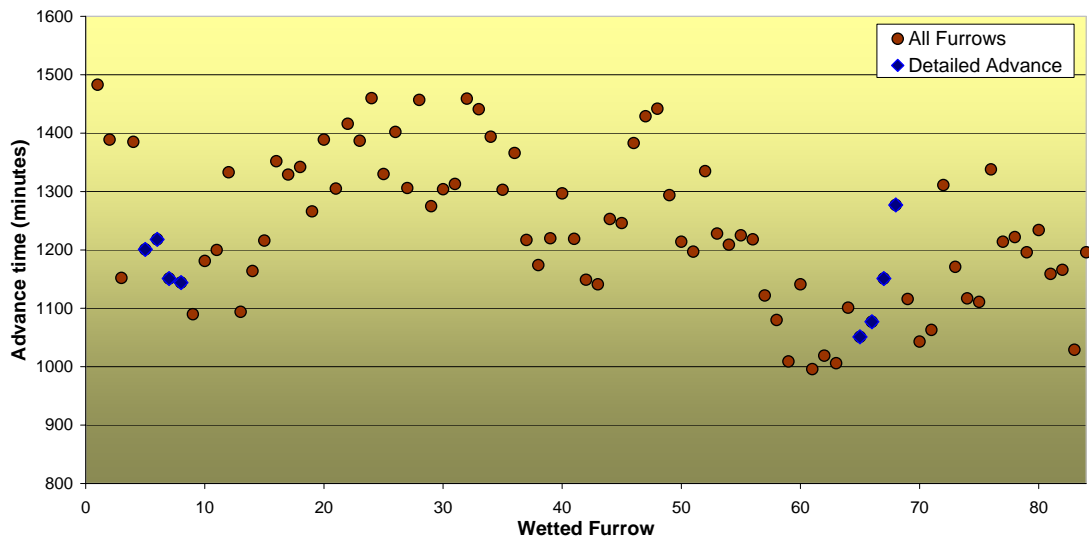


Figure 17. Time taken to reach final advance point (761 m) for Lagoon

Calibration & Estimation of Infiltration Curves using IPARM

Infiltration parameters were estimated using IPARM from the advance data and constant inflow rate for all furrows with two or more measured advance points. For furrows 5, 30 and 67 the infiltration parameters were estimated using the advance and runoff data collected during the storage phase (i.e. times less than 1410 minutes). The resulting infiltration curves are shown in Figure 4. The surface storage was estimated using the average wetted furrow dimensions and the upstream flow depth of 50 mm resulted in a Manning's roughness value of $n=0.03769$.

The infiltration curves produced from two advance points (furrows 21-40) have widely varying shapes (Figure 18). However, those estimated using increased numbers of data points have both reduced variability and relatively uniform shape. The use of runoff data to estimate the infiltration parameters appears to standardise the curves further. This demonstrates the apparent variability that can arise through reduced field data. The infiltration curves from two advance points had increased variability at short and long opportunity times (Figure 18). However, they tend to have reduced variance and match the curves estimated from the detailed measurements at opportunity times between 800 and 1200 minutes. These two time values correspond approximately with the advance times at the middle and final advance points, respectively. Hence, the infiltration curves estimated from the two advance points should not be used to predict infiltrated depths at opportunity times that widely depart from the measured advance times.

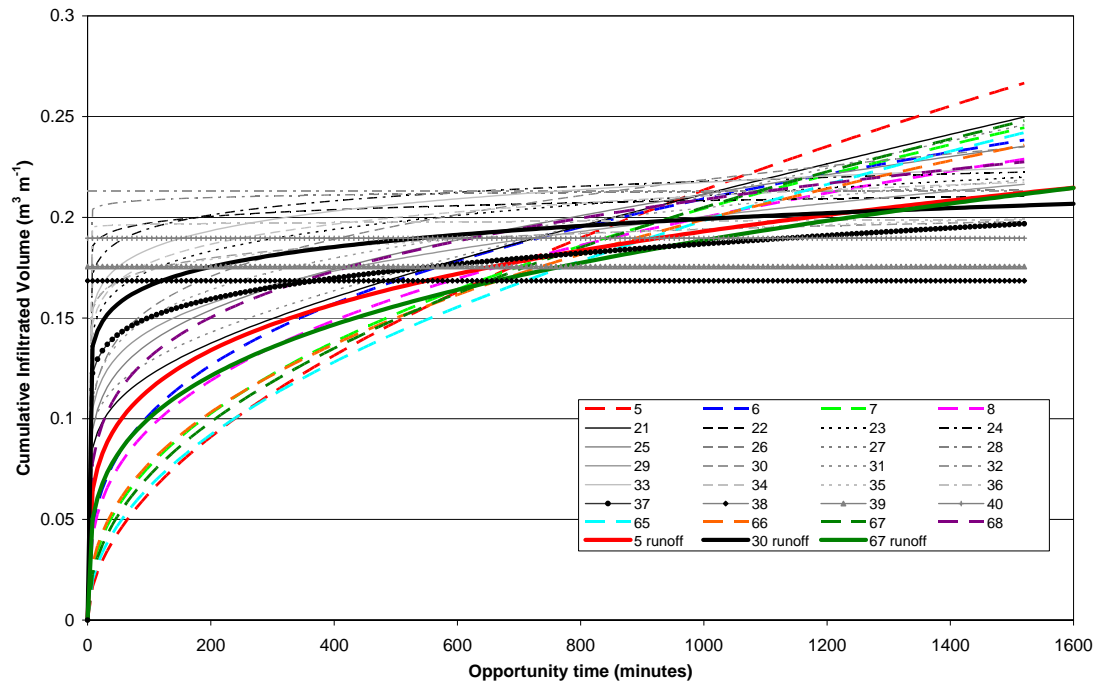


Figure 18. Infiltration curves for Lagoona estimated using IPARM

Predicting Infiltration Parameters using the Final Advance Time

The plot of final advance times (Figure 19) shows that the nine furrows with sufficient data for operation of IPARM do not cover the variance seen in the field. Simulation and optimisation based on these furrows alone will not be able to predict the range of applied depths and runoff volumes that would occur in the field. Hence, it is necessary to identify the soil infiltration rates for additional furrows. The process requires one advance measurement for each furrow, in this instance, the time for the water to traverse a distance of 761 m. The infiltration curves estimated using advance and runoff data (furrows 5, 30 and 67) were used as the known infiltration curves since they should be the most accurate. These selected furrows are reasonably spread throughout the variance in final advance times with probabilities calculated from $ZVal_{VB}$ of 40.9, 72.1 and 25.7%.

The infiltration parameters were predicted for all furrows with less than three advance measurements, excluding furrow 30 (i.e. furrows 1-4, 9-29, 31-64 and 69-84). It is presumed that the remaining furrows contain sufficient advance measurements for the IPARM inverse technique. The resulting predicted and IPARM estimated infiltration parameters are shown in Figure 5. The predicted infiltration curves take on a similar shape to that of the three base furrows. The CV between the resulting curves declines slightly with increasing opportunity time, the CV in cumulative infiltration is 11.6%, 10.0% and 9.6% at 400, 800 and 1200 minutes respectively. The infiltration rates vary (CV) by 19.7%, 25.5% and 29.3% at 400, 800 and 1200 minutes, respectively.

Optimising Performance

The Lagoona irrigation was optimised using IrriProb. The field was optimised according to two main criteria. The first objective (Obj 1) was to achieve both a requirement efficiency (RE) and distribution uniformity of the root zone (DURZ) of 90%, while maximising the application efficiency (AE). The second objective (Obj 2) is to maintain a RE of at least 95% and AE of 70% while minimising the average depth of deep percolation (D_{DD}). For this field it should be possible to attain a higher level of irrigation adequacy as the infiltration curves exhibit low variance (Figure 19). Hence, the two objective functions were repeated using a $RE > 99\%$ criteria (i.e. Obj 1.b and Obj 2.b).

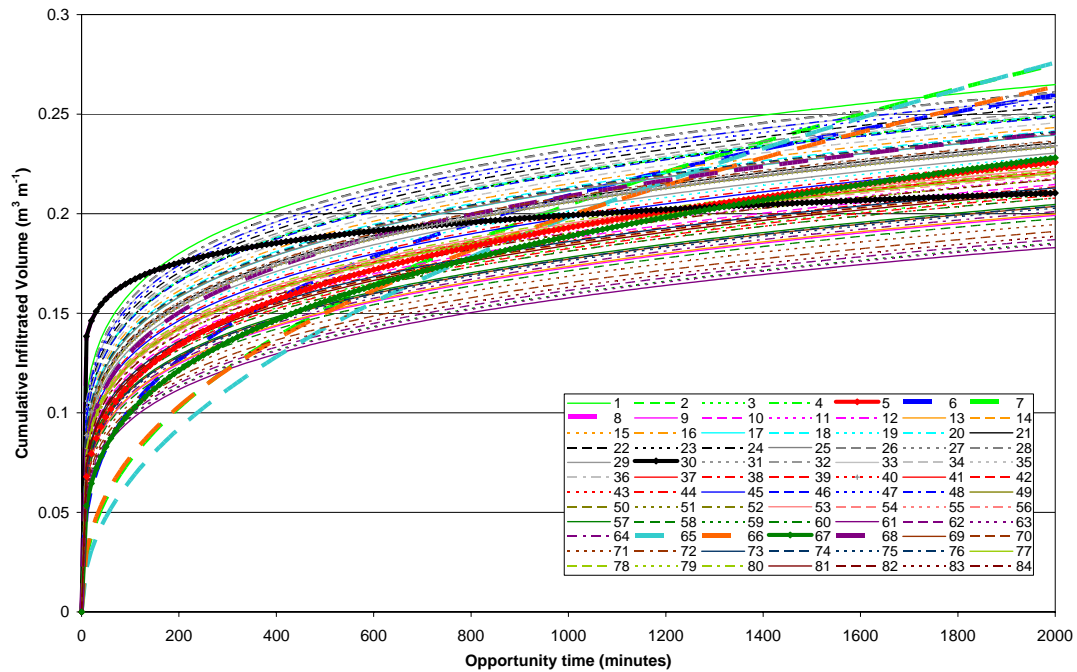


Figure 19. Predicted infiltration curves for Lagoon
(IPARM calibrated furrows are 5-8, 30 and 65-68; predicted infiltration in remainder)

Current Performance

The simulation was carried out by IrriProb using the infiltration parameters identified by IPARM for nine furrows and predicted infiltration parameters for the remaining furrows. The value of Manning n used in the simulations was maintained at the same value used to estimate the infiltration parameters (0.03769). The resulting field simulation reproduced the final advance point (761 m) over the 84 furrows with a root mean square error (RMSE) of 35.2 and average deviation of +4.63 minutes. Further attempts to calibrate a field wide value for n was not necessary. Simulation trials found that at value for $n = 0.03$ the RMSE increases to 36.9 and average error changes to -11.76 minutes whilst $n = 0.04$ results in an RMSE of 35.9 and average error of +9.47. It was found that small changes to Manning n improved the fit to the final advance point, but compromised the ability to predict other advance points (for those furrows with additional advance measurements).

The whole field simulation indicated that the Lagoon field had high irrigation adequacy with a RE of 98.9 % whilst also having relatively high efficiency (AE = 78.2 % and AER = 85.7 %). The irrigation also had high uniformity, with a low quarter distribution uniformity (DU) equal to 83.6% and DURZ = 96.6 %. The average runoff per furrow was 14.75 m³, and the average depths applied to the root zone and deep drainage were 82.1 mm and 13.8 mm, respectively. As the performance of the Lagoon field is considerably high (Table 1) only minimal performance gains can be expected through optimisation of irrigation management. The AE and RE only vary by 1.3 % (CV), but other terms experienced greater levels of variability (e.g. CV = 6.7 % for DU and CV = 6.2 % for AER). The majority of the variability manifests itself within the predicted runoff (CV = 72.1 %) and deep drainage (CV = 50.3 %) volumes.

It was noted that the simulations provided poor predictions of measured runoff volumes (i.e. 19.6 m³, 15.3 m³ and 21.5 m³ compared to measured values of 50.7 m³, 41.3 m³ and 22.0 m³, respectively). However, the runoff accounts for less than 9 % of the total inflow volume. In addition, the measured outflow hydrographs far exceed the time of cut-off suggesting that the flumes may have been submerged during the later stages of the irrigation due to restricted drainage.

Optimising the Time to Cut-off

Firstly, the optimisation process considered the potential to improve irrigation performance by altering the time to cut-off (TCO) alone. The inflow rate was constrained to the measured discharge of 1.95 L s^{-1} and all other field characteristics are as measured. The field was simulated for inflow times ranging from 200 to 2000 minutes and the optimisation tool within IrriProb was used to determine the optimal cut-off time. Obj 1.a shows that a minimal increase in the AE is possible by reducing the inflow time to 1303 minutes with a slight penalty in the RE and DURZ (Table 14). In this case the reduced uniformity indicates that the water would not reach the end of the field within a small number of furrows. Objective 1.b suggests that the TCO should be increased to 1420 minutes to ensure adequate water application over a greater proportion of the field.

Objective 2 demonstrated that it is possible to reduce the average deep drainage by 2.9 mm and increase the AE to 85% by decreasing the inflow cut-off time to 1247 minutes. However, to maintain the same RE as measured in the field, the inflow time must be restored to the higher value of 1420 minutes (Obj 2.b). This time is almost identical to the measured irrigation time (1410 minutes). Hence, there is minimal potential for improvement of the irrigation performance over measured conditions by altering only the time to cut-off.

Table 14 Optimising Lagoona by time to cut-off

	Objective	TCO (min)	AE (%)	AER (%)	RE (%)	DU (%)	ADU (%)	CU (%)	DURZ (%)	Inflow (m ³)	Run. (m ³)	D (mm)	DRZ (mm)	D _{DD} (mm)
	Current	1410	78.21	85.74	98.87	83.57	0.00	89.65	96.57	166.4	14.75	95.9	82.1	13.8
Obj 1.a	RE>90, DURZ>90 Max AE	1303	82.80	87.37	96.80	78.59	0.00	87.48	90.08	153.9	8.28	92.2	80.3	11.8
Obj 1.b	RE>99, DURZ>90 Max AE	1420	77.78	85.57	99.00	83.89	0.00	89.79	96.98	167.6	15.36	96.2	82.2	14.0
Obj 2.a	RE>95, AE>70 Min D _{DD}	1247	85.03	88.54	95.00	74.13	0.00	85.57	84.26	147.1	6.09	89.6	78.8	10.8
Obj 2.b	RE>99, AE>70 Min D _{DD}	1420	77.78	85.57	99.00	83.89	0.00	89.79	96.98	167.6	15.36	96.2	82.2	14.0

Optimising Inflow

Assuming that it is possible to alter siphon sizes and/or head ditch conditions, further increases may be possible through altered inflow discharges. This time the field was simulated using inflow rates between 1 and 7 L s^{-1} and inflow times between 400 and 1600 minutes. The first optimisation, Obj 1.a provided an increase in the AE and demonstrated that the deep drainage depth could be reduced by 50 % through increased inflow rates (Table 15). Attempting to increase the irrigation adequacy (Obj 1.b) causes the AE to drop as the runoff volume increases from measured conditions. However, the behaviour of the application efficiency with recycling (AER) indicates that this decline in efficiency can be overcome if the tail-water is recovered.

In all the optimisations of the Lagoona field thus far, the absolute distribution uniformity (ADU) has been equal to zero. An ADU = 0 % indicates some part of the field, no matter how small has received zero application. Optimising the field based on objective 2 (both 2.a and 2.b) improved the ADU to values greater than 75%. Hence, no part of the field has received less than 75% of the average applied depth. This example illustrates the problems involved with using the RE as the solitary indicator of irrigation adequacy as the RE of obj 2.a was actually less than the measured irrigation. It is possible to improve the uniformity and AER by increasing the inflow discharge.

However, the ability to increase inflow rates is limited where the irrigator is attempting to achieve perfect RE.

The results suggest two possible methods to improve irrigation performance. Firstly, the inflow discharge can be increased slightly to 3.17 L s^{-1} for 790 minutes to reduce the deep percolation loss. The second scenario, where the irrigator can re-capture the tail water, the inflow rate can be further increased to shorten the advance phase. This will ensure adequate application at the downstream end of the field and improve the overall uniformity of applied depths. The increase in inflow volume associated with obj 2.a and obj 2.b is misleading. After subtracting the water recovered from the runoff (recycling efficiency of 85%), the net depth of water applied to field was found to be 86.4 mm and 95.9 mm for obj 2.a and obj 2.b, respectively compared to the measured irrigation at 97.0 mm.

Table 15 Optimising Lagoon by time inflow rate and time to cut-off

	Objective	Q (L s ⁻¹)	TCO (min)	AE (%)	AER (%)	RE (%)	DU (%)	ADU (%)	CU (%)	DURZ (%)	Inflow (m ³)	Run. (m ³)	D (mm)	D _{RZ} (mm)	D _{DD} (mm)
	Current	1.953	1410	78.21	85.74	98.87	83.57	0.00	89.65	96.57	166.4	14.75	95.9	82.1	13.8
Obj 1.a	RE>90, DURZ>90 Max AE	3.170	790	83.67	91.90	96.71	84.24	0.00	89.95	91.01	152.2	14.74	86.7	80.3	6.5
Obj 1.b	RE>99, DURZ>90 Max AE	2.150	1311	76.65	86.21	99.30	85.27	0.00	90.43	97.88	170.5	19.20	95.6	82.4	13.2
Obj 2.a	RE>95, AE>70 Min D _{DD}	5.820	480	73.11	93.16	95.15	86.41	75.79	91.05	90.12	171.3	40.41	82.4	79.0	3.4
Obj 2.b	RE>99, AE>70 Min D _{DD}	3.280	933	70.36	88.31	99.04	87.03	75.33	91.60	97.09	185.3	39.13	92.1	82.2	9.9

Conclusions

The Lagoon field trial has provided valuable information describing the spatial variation in infiltration that occurs within a single irrigation event. Autoregressive analysis has shown that the advance times and therefore infiltration rates are spatially dependent. Statistical analysis of the variability in final advance times indicated that furrows subject to machinery traffic had advance times that were increased by approximately 42 minutes (3.4 % faster) than uncompacted furrows. The effect of soil compaction only explained a small part of the total variance observed. Statistical analysis of the spatial variability indicated that maximum benefit is obtained from the measured data where the sampled furrows are located at least 20 m apart. However, such sampling is not implemented in current measurement procedures and not practical with the existing suite of measurement tools.

The Lagoon field trial demonstrated the use of the IPARM procedure to estimate accurate infiltration curves from field measurements. By combining this information with simple single advance point measurements it was possible to predict the infiltration curves across the entire field. Irrigation simulation indicated that the field was managed under a near optimum combination of inflow rate and time. Hence, there was minimum potential for improvement. Optimisation using IrriProb has suggested that the uniformity can be improved via the adoption of increased inflow rates.

4. Discussion

It has long been the convention that good scheduling requires supplying the crop with as much water as it can transpire (Dale 2007). However to maximise irrigators' returns from their water, transpiration must be considered amongst an array of irrigation management variables and farming production needs, such as; application efficiency, distribution uniformity, control of vegetative growth, minimisation of offsite movement of soil and chemicals and capture of in-crop rainfall. In recent times measuring irrigators' returns on productivity of irrigated cotton is not only recorded as yield in bales per hectare, but also as an efficiency index of bales per mega litre. These results show that there is room for improvement in current surface irrigation practices in the DVIA and a need for guidance to achieve gross production water use indices (GPWUI) that rival other irrigation areas. These results show that optimum efficiencies can be obtained by measuring application depth and uniformity and by modifying some long accepted practices. All growers find it challenging to measure water volumes and movement around the farm. If you cannot measure it you cannot manage it, however no matter the difficulty, benchmarking of current performance is needed.

Improvements to furrow irrigation such as basic standards to optimise furrow design and operation are needed. Collation of best practice, rules of thumb, validation and greater extension is the way forward (Roth, 2007). In moving forward in the DVIA there are a number of modifications to infrastructure and irrigation management that can be made to improve furrow irrigation performance. The most cost effective improvements are made possible through management changes. Three irrigation management changes which can be measured and modified are infiltration characteristic, inflow rate and time to cut-off.

Infiltration characteristic is influenced by the soil moisture content at the time of irrigation and can change over the season as seen in the infiltration curves for Lagoona. High infiltration rate occurs during crack fill after which it quickly decreases. Typically by the end of the season this process has changed because overall infiltration rate has decreased. Stretching the time between irrigations increases the soil moisture deficit, which generally slows the irrigation water advance rate, which may have a detrimental effect on overall performance, unless inflow rates and time to cut-off are adjusted appropriately to cope with seasonal change in performance and/or soil moisture deficit management decisions.

Many irrigation events can be improved through simply modifying the total irrigation time, however it is more usual to make a change in both time to cut off and inflow rate to optimise irrigation performance, which is generally undertaken by intensive measurement and modelling. An appropriate initial guideline, as given by Carter and Grabham (2004) could be:

- Compare total inflow and application requirement (Deficit).
- Investigate commercial analysis and modelling services.

4.1 *Application requirement*

The target deficit is the amount of water that the irrigation event aims to supply. Typically, surface irrigation events aim to refill the entire root zone to field capacity so that the interval between irrigation events is as long as possible. In this case, the target deficit would be equal to the total soil moisture deficit (the difference between field capacity and the current moisture content). The soil moisture content at which cotton begins to stress (-100kpa), the readily available water (RAW) content or refill point, is typically used as the target deficit for furrow irrigation systems. Whilst this strategy to refill the soil profile to field capacity may be appropriate, production is compromised. Especially when an irrigation event is closely followed by a rainfall event, as the profile is already full and the rainfall may cause, initiate or extend waterlogging, runoff and or water loss below the root zone. Drainage occurs when more rain or irrigation is added to soil than there is empty storage

capacity to hold it. Drainage risk can be reduced by maintaining sufficient empty storage (soil water deficit), as a buffer. Some drainage, or leaching fraction, is needed to avoid salt build-up in the soil profile, although this should largely be provided by rainfall (Silburn, 2004). For example in the Emerald Irrigation Area and to the south on the Dawson River, irrigations conducted during the 2004-05 season on deficits up to 87mm incurred considerable deep drainage (20-65mm) and deficits >18mm were sufficient to capture rainfall events without deep drainage losses (McHugh and Pendergast 2004). For the farms in the DVIA in the same year, deficits were largely close to the RAW content, but the application volume far exceeded these values, running the real risk of offsite chemical and soil movement early in the growing season and during storm producing runoff events (Waters, 2001; Carrol *et al.*, 1995). Exceeding the application requirement reduces capacity for rainfall utilisation, increases water logging and a cycle of early irrigations. In 2005-06 RAW was vastly under utilised, caused by early and frequent irrigations, which could have also lead to the real risk of further offsite losses of water, chemicals and soil, waterlogging, loss of production and excessive vegetative production. The dry weather pattern and the likelihood of limited irrigation water in 2006-07 was an exemplar season in which the importance of the deficit was highlighted. RAW could have been fully utilised and application volumes applied to strictly replenish the deficit. Through careful monitoring and a deficit strategy, enough water could have been saved (~70mm in both sites) for a further irrigation at a critical point later in the season.

To further highlight the significance of deficit management, Freebairn (2007), when reporting on the GRDC funded Pesticides in Catchment Kit Risk Assessment Tool suggested: “*growers should keep several factors in mind when considering risks of offsite chemical movement, including that; awareness of risk factors leads to better decision making; runoff risks are lower on deeper, drier and more permeable soils; soil erosion risk is lower with more cover; herbicide, prone to movement in runoff, declines with time after application*”. These risk factors promote a deficit irrigation strategy for the DVIA.

A deficit strategy aims to only partly refill the soil profile to improve the likelihood of capturing rainfall and also allow manipulation of crop stress levels. This strategy of deficit irrigating results in more irrigation events per season, but a greater ability to capture rainfall, manages plant growth and facilitates irrigation performance. The frequency of application is typically a balance between the amount of moisture in the soil, the likelihood of rain, crop development and the labour requirements for irrigation. Often irrigation intervals are stretched, so that fewer irrigations are required during the season and hence less total labour will be required. However, stretching irrigation events can have a negative impact on the performance of surface irrigation systems, as a soil’s properties vary with moisture content (deficit), and surface irrigation systems rely on the soil as the application system. Stretching irrigation events will decrease the rate at which irrigation water advances down the furrows (the empty profile takes longer to fill), subsequently affecting the uniformity of application and the total application amount required to fill a certain deficit.

On farm irrigation assessments evaluate how accurately and uniformly water was applied during an irrigation event. According to Sarah Hood in the project case studies, accuracy and uniformity in irrigation implies a target and that target is the deficit, which is the key to irrigation performance. The irrigation performance implications are outlined in the project case studies and in the case of ‘Girraween’, it is in the format in which it would and should be presented to and discussed with the grower.

A deficit should typically not be more than the RAW in the effective root zone (mm/m), which generally would approximate 8-10 days of peak cotton water use in the clay soils around the Theodore District, assuming the active root zone is 1m deep during the latter part of a season. According to the soil analysis for PAWC of numerous soils within the region, RAW is nominally quoted at 0.5 of PAWC and in some cases these values are high for the soil textures in the area. Generally, for light to heavy clays, soil moisture content between -10 and -100 kPa should be in the range of 60–80 mm/m of active root zone.

4.2 Inflow rates

Improvements in irrigation performance significantly depend on distribution uniformity of the irrigation water. Uniformity relates to the evenness of irrigation application and is an important measure of irrigation system performance, which ultimately affects the uniformity of crop growth and yield. Variations in irrigation uniformity should be avoided to ensure even crop production, However extra water is often run to help make up for non-uniformities, so that the entire crop is watered adequately, as was the case with extended run times at Lagoon and areas of the DVIA. Consequently some part of the field will receive too much water, resulting in waterlogging, which has an even greater negative impact on yield than under-watering part of the field. Some evidence of that can be inferred from the NDVI imagery used in this study to select farms that may benefit from irrigation optimisation.

Distribution uniformity can often be improved through changes to flow rate and watering interval. Generally this means that water has to get to the end of the field quickly and then supply to be switched off to minimise the opportunity time for drainage in the head ditch area, particularly on “leakier” soils. Improvements in DU result in more even crops and the associated benefits including fertiliser efficiency. Surface irrigation events in the region should have a distribution uniformity of at least 75%.

In the first season at Lagoon, DU generally exceeded 75 % for both sites. However the Control site with low inflow rates was in the low 90s, but conceded considerable runoff losses to achieve such high percentages in application uniformity. Very high infiltration rates in the Treatment site suggest that the advance rate generated by the 4 L/s inflows was not fast enough, (extended inundation /opportunity time) consequently, considerable water was lost to deep drainage. In contrast, final infiltration rates in the last hour of early and late season irrigations of the Control site were much less than average advance, which lead to excessive runoff losses due to the extended TCO. The infiltration curves for the Treatment site indicated that initial crack fill phase continues over the period of the irrigation, whereas in the Control site, soil permeability reduces following crack closure ahead of the slowly advancing water.

With reorientated and re-sized fields the phenomenon continued into the following seasons with the distinctly different infiltration curves and final infiltration rates between the two sites. Inflow rates for the Treatment remained similar at around 4.0 L/s with DUs averaging 82 %, while conceding significant deep drainage due to the higher % of inflow satisfying infiltration at the expense of the advance rate. The Control site inflow rates were reduced by about 1 to 1.54 L/s on average, but because of the low final infiltration rates (1.7-2.0 L/h) compared to the advance rate, high DUs were maintained at the expense of considerable runoff.

In the 2006-07 year at Lagoon, the Treatment and Control sites were reconfigured so that they were symmetrical. The increased flow rates (5.5 L/s) in the Treatment changed the previous scenarios little. However, the whole of field variability analysis case study conducted by Malcolm Gillies confirmed the nature of the irrigations, where if the irrigator can re-capture the tail water, the inflow rate can be increased to 5.8 L/s to shorten the advance phase. This will ensure adequate application at the downstream end of the field and improve the overall uniformity of applied depths. The case study confirms that the application strategy for the Treatment site was the most correct for these years, even though the higher flow rates tended to mobilise more nutrients and chemicals and therefore had higher concentrations in the tail water from this site compared to the Control site. Therefore the time to cut-off becomes relevant not only in reducing the recession phase, but reducing runoff volume and the potential movement of high concentrated solute moving off the field.

4.3 Time to cut-off

In the wider DVIA area reduction in TCO was the key to improving irrigation performance. Inflow rates on selected properties were medium at 2.5-4.5 L/s with very high DUs, but all conceding considerable losses to runoff and deep drainage due the period of field inundation. Inflow rates for properties on the Dawson River given in the case studies were similar to the DVIA farms, but their irrigation run times of those on the river were less than half those in the DVIA, resulting in very high DU and E_A on the river farms (after recycling). E_A in the DVIA was very poor due to the losses they were experiencing, which was significant, because reclaiming runoff water is not possible on some farms in the irrigation area. Generally, by reducing period of inundation (opportunity time) application efficiencies will be increased.

Opportunity time for infiltration consists of two phases the advance and the recession. As discussed before the advance phase is largely driven by the inflow rate, infiltration characteristics, field characteristics and the length of the irrigation. The recession phase is driven by the same parameters, but does not commence until after irrigation syphons have been stopped. It is this volume of water flowing down the field that satisfies the field water requirement that was not satisfied by the advance and which in some cases, allows the irrigator stop the irrigation inflow before the advance reaches the end of the field. This strategy was not tested at Lagoon nor in the DVIA, but the “no runoff scenario” was modelled under high flow and current flow rates for three farms in the DVIA which demonstrated that by reducing opportunity time by up to 3.3 hours, runoff can be removed from the irrigation event, whilst maintaining DU, E_R and raising E_A by 20%. Data sourced from Raine and Walker (1998) achieved the same result, that was, by maintaining the same inflow rates and initiating time to cutoff one hour prior to the water reaching the end of the field. This is not to say that this strategy should be adopted as a simple irrigation performance solution to minimise runoff, because as Carter and Grabham (2004) highlighted, in some cases water requirement at the bottom of fields may not have been satisfied, that is DU could be reduced, hence the need to investigate commercial analysis and modelling services before adoption.

4.4 Volume Applied

The aim of a furrow irrigation event is to replenish the soil moisture deficit as discussed previously. Irrigation applications that are significantly larger than the deficit result in water being lost as runoff or deep drainage and the associated movement of sediments, nutrients and contaminants. Volume applied should not be more than the deficit, except in a dry year there may be a requirement for a leaching fraction. However in a normal (wet) year a buffer will be required to capture rainfall as in deficit irrigation. Obviously the total volume to be applied requires an understanding of the deficit at each irrigation, perhaps from ET_0 data, or soil moisture probes which may be useful following data transformation to give a quasi-calibration. Notwithstanding the previous discussions on uniformity, the total amount applied has the greatest impact on potential losses. Applying too much water directly increases the likelihood of waterlogging and the amount of water lost as deep drainage or tailwater.

Varying the application amount in a furrow system involves changing the siphon size, siphon head measurement and time to cut-off. Therefore it is not the total volume to be applied that takes precedence, but at what rate it is delivered and over what time. So to say the aim of a furrow irrigation event is to replenish the soil moisture deficit is an over simplification. The testament to an over simplification could be the over irrigation in all but a few of the irrigations assessed throughout the region over the last three years. When the deficit is known or an arbitrary one of 50 mm was in place from ET_0 estimates the volume applied was not adjusted hence the considerable losses illustrate in the water balance figures of the first two seasons at Lagoon and those losses described on five other farms around Theodore. The two exceptions to the above were those in case studies, where infiltrated volume was very well matched to the deficit, but these farms have recycling

systems, so the applied volume in excess of the target deficit that generated runoff was captured for reuse.

4.5 Volume of Runoff

Runoff is a particular issue for farms within the DVIA due to a lack of tailwater recycling facilities. It is possible to achieve adequate uniformity with sufficient infiltration of water without running tailwater for significant periods of time or if at all under deficit irrigation practices. With the correct combination of flow rate, the siphons can be pulled before the advance reaches the end of the field to reduce the volume of tailwater. The result is not only a reduction in the volume of tailwater and hence the volume of contaminants leaving the field, but also a potential reduction in the amount of water required for application. The strategy requires an understanding of volume applied, the deficit or a guideline of proportion of runoff for different flow rates and run times from irrigation simulations.

The volume of contaminants that left the fields under trial conditions at Lagoon could have been easily replicated throughout the area where recycling infrastructure was not available. The practices engaged at Lagoon in many ways are practiced in the wider area, as is evidenced by the runoff that was recorded at the other sites around Theodore. The inflow rates used in the wider area (average 3.4 L/s) were marginally less than the high rates (3.9 L/s) used in the treatment site at Lagoon and considerably higher than the control (1.5 L/s) and the same as those used in Emerald by Bhattarai *et al.*, in 2003. Hence the level of nutrient and chemical concentrations could have been as high as those experienced at the trial site in 2005-06 (Soil: 1 t/ha, N: 4.4 kg/ha, K: 5.7 kg/ha, P: 0.5 kg/ha, Diuron: 18.3 g/ha) and at Emerald, 4.563 t/ha of soil in 2003). If this were the case, then considerable offsite movement could have been occurring. Or at the least there was the potential for it to occur, especially in the first few hours of irrigations and especially in early season irrigations, which also coincides with the storm season (normal years), a combination that has been recorded as high risk for the environment (Waters, 2004; Carrol *et al.*, 1995; Freebairn, 2007). The cotton industry has invested significant R&D funds over the past decade to address the issue of off-site movement of pollutants. Key findings from the work identified the high-risk period as early season and highlighted the importance of storms and sediment in moving pesticides off-site and the importance of groundcover in reducing movement.

4.6 Deep Drainage

Opportunity time is the length of time that irrigation water is applied to the soil surface and is available for infiltration. Opportunity time is the difference in time between when irrigation water first reaches a point (advance) to when the last free water drains from that point (recession). The likelihood of deep drainage increases with opportunity time, as the potential amount of infiltration becomes larger, thus opportunity time can be controlled by time to cut-off. Deep drainage results in a loss of irrigation water and potential movement of nutrients and chemicals into groundwater and river systems. Surface irrigation events in the region should attempt to minimize the likelihood of deep drainage occurring due to irrigation application, because it has been found that common furrow irrigation practices cause substantial deep drainage under cotton fields in Queensland (McGarry, 2007 Pers. Comm.). Farms in the wider Fitzroy Basin that were considered to be optimally managed lost 100-650 mm of irrigation water to deep drainage annually (McHugh and Pendergast, 2004). These farms were on similar soils, and one in particular was 500 m in length, with irrigation times of around 600 minutes, therefore quite similar to those properties around Theodore, except their irrigation runtimes were initially 2-3 hours longer than reported in the EIA. As indicated in the results, the majority of farms assessed in Theodore were vastly improved when time to cut-off was reduced to near or less than 500 minutes. According to the whole of field assessment at Lagoon optimum time to cut-off was 480 minutes. Also in the case studies optimal irrigation was achieved with intensive management in less than 300 minutes. Studies in three

different production regions of southern Qld and NSW demonstrated similar results of considerable savings in deep drainage (15 mm/irrigation in one case) by reducing inundation time (opportunity time) from the typical management times of 990, 692, and 745 minutes down to 396, 245 and 570 minutes, respectively (Carter and Grabham, 2004; Raine and Walker, 1998; Fairfull, 2004). “Water should be on and off the field in 6 hours”, this is currently touted as a proven method for irrigation improvement (Roth, 2007). For the DVIA opportunity time should be less than 500 minutes, and although this figure fits well with the eight hour shift concept that farmers tend to prefer, it may not be the most efficient time, but an upper limit for scaling simulations in a modelling process that is essential for determining the site specific characteristics of an irrigation event.

4.7 Application Efficiency

Application efficiency is the ratio of water that is available to the plant compared with that delivered to the field. The higher the efficiency, the greater proportion of applied water is available to the crop, indicating fewer potential losses of water and water borne contaminants. The target efficiency value should be higher when recycled tailwater is taken into account as this water can be re-used, however as stated on numerous occasions, many growers in the DVIA cannot recycle tailwater. Therefore, those growers should operate a “no runoff” scenario and employ deficit irrigation management. If this scenario was achievable and an accepted guiding principle, then E_A would be 100 %, in that, all water applied would be available for crop use. For example, in the extra sites measured around the DVIA the simple process of reducing TCO raised E_A by at least 20 % and in one case it was doubled to 90 %, with fine tuning 100 % E_A is achievable.

In practical terms perfect E_A is probably not achievable on the vast majority of farms because of variability in: (a) inflow across a siphon set, (b) infiltration characteristics and (c) furrow condition across the field. Initial observation of the advance completion times from Malcolm Gillies work indicated that the furrows with detailed measurement experienced advance rates that were representative of the remainder of the field. However, the variation in advance times that existed did not appear entirely random. As the case studies show, the wetted furrows tended to have slower advance rates than the other furrows, probably because of breakouts into adjacent furrows or inflow variation across the siphon set, although head was largely unchanged if not marginally less on the furrows with increased advance rate. Part of the variation between closely spaced furrows is caused by compaction from machinery operations, hence there was considerable difference in advance times between wheeled and non wheeled furrows, 47 minutes at Lagoon on permanent 1m ridge till system and 90 minutes difference on a 2 m permanent bed system.

Rarely are furrows or sets of furrows managed individually across the field and it is very difficult to optimise E_A and other efficiency parameters for such cases routinely. However, Mr Gillies’ methodology of using extra advance points across the field and analysis with “IrriProb” provides a process to deal with this variability. Unless particular syphons (various diameters) are keyed into field variability to provide a range of appropriate inflow rates, runoff will be generated from the faster furrows while waiting for the slower ones, especially in the situation of high inflow rates that exceed the average advance, as outlined by Sarah Hood in the Acacia case study. Once runoff commences water is lost thorough conveyancing (about 15%) in the recycling infrastructure, should it exist. So with recycling E_A can be no more than 85%, without recycling the industry standard aims for an E_A of >70%. Both application efficiency and distribution uniformity of furrow irrigation systems can only be determined through an intensive measurement and modelling process.

4.8 Yield and Cotton Quality

Distribution uniformity has a significant impost on cotton production, either in terms of oxygen stress from waterlogging at head end of the field and/or water stress at the other. Relatively reasonable DUs (high 70s to low 90s) in both the Treatment and Control sites in 2005-06 caused a considerable difference in yield (1.5 -2.5 b/ha) between the top mid and tail sections of the field.

Yield variation of 7.4, 8.9 and 7.9 b/ha between the top mid and tail section of cotton fields in Emerald irrigation area (unpublished data) were also attributed to DUs and E_A that were not dissimilar to those measured at Lagoona. In the case of Lagoona, if the irrigation had been uniform and hence the crop more uniform, then an extra 1-1.5 b/ha on average could have generated extra returns of \$4200 on the 7 ha trial site at \$400/bale.

Cotton quality up and down the field was variable, and also attributed to spatial variation in irrigation performance. Discounts at the gin for the crop probably did not apply, because the crop was harvested along the rows and therefore any variance would have been neutralised. However, overall premium could have been raised with improvement in DU.

The satellite based NDVI imagery used in this study was very beneficial in identifying farms with variation in crop vigour. Although this variation, once identified, cannot be rectified in the same season because the plant structure is already in place, it can be used as an indicator of irrigation performance modification, but not routinely. On the other hand, terrestrial based systems (vehicular mounted or airborne modes) could be utilised in a routinely tactical mode during the production season to determine if spatial variability in crop vigour was related to irrigation performance.

4.9 Benchmarking

The application efficiency of the furrow systems that were benchmarked elsewhere in Australia indicated many systems can be improved by manipulating lengths and slope of furrows with appropriate flow rates and cut off times. A three-year study of furrow irrigation systems by NSW Agriculture in the Macquarie Valley found furrow conditions and variable siphons flow rates had considerable impact on the effectiveness of an irrigation event. While field lengths varied from 450 to 1300 m, the time to cut-off ranged from 3.5 to 26.0 hours and the total volume delivered to each furrow ranged from 0.01 to 0.30 ML. Within a single siphon set, flow rates were found to vary from less than 0.5 L/sec to 2.8 L/sec (Tennakoon *et al.*, 2004). This widely varying set of data compares with that found in the DVIA to a certain extent.

Variation in inflow rates was apparent within siphon sets at Lagoona and time to cut-off ranged from 3–32 hours across all irrigations for the river and scheme operators assessed. Mid season irrigation time in the DVIA ranged from 9-14 hours, but there is certainly enough anecdotal evidence that suggests there is considerable variation here as there is elsewhere in the industry. Therefore benchmarking is important in determining the application efficiencies produced from the various combinations of deficit (furrow condition), inflow rate, and time to cut-off employed in delivering water to the cropping zone. This typical variation in application characteristics has a considerable effect on water use efficiencies. As an example, GPWUI at Lagoona was 0.51 bale/ML in the first season followed by 1.54 and 1.20 in the following two seasons. The difference largely resulted from the varying volumes of applied water plus rainfall during each season totalling 13.23, 6.82 and 6.37 ML, respectively. The industry GPWUI average from 2004 data across all major production area was 0.79 bales/ML (Tennakoon *et al.*, 2004) and as demonstrated at Lagoona in the second season, reducing runoff by 2-3ML/ha and raising yield by 3 b/ha, GPWUI was twice that of the industry average. In terms of WUI, 2 bales/ML appears to be the target where an irrigator seeks to produce 2 bales for each ML of applied irrigation water.

In terms of reporting on a field benchmarking assessment, the first thing that a consultant and grower should look at is the comparison between infiltration and deficits. Most discussions centre on deficits and generally the concept requires further attention as a particular deficit is the key upon which a report to a grower would hinge. The infiltration curve describes the soil infiltration characteristics during each individual event and is a very important tool when discussing results and reasons for the measured efficiencies. They are also important for discussions about time to cut-off and whether a system change may be necessary. In general terms growers just want to know how

good or bad they are and what they should be aiming for. The consultants in the region felt that targets for the various efficiencies should be provided and compared during a benchmarking process. Strategies for improvement in efficiencies, where necessary, should be provided and must be practical. Therefore there is a need for discussion between agronomist and client to focus on the possibilities so that improvement scenarios make sense.

5. Guidelines

The following were not tested on either Lagoon or in the DVIA due to the lack of irrigation water in the third and final year of the project. An opportunity exists to move forward with a benchmarking and performance improvement program in 2008 utilising the strategies in this section.

5.1 Amount of application

Amount of application of irrigation water is a function of the inflow rate over the total time of the irrigation and these two variables have the greatest impact on runoff and deep drainage below the root zone. Minimising losses involves changing: siphon size, the supply head and/or time to cut-off.

5.2 Application efficiency

Application efficiency (E_A) is the true efficiency measure that relates the amount of water supplied to the amount of water available to the crop and is represented as a percentage (%). $E_A = \text{Irrigation water available to the crop} / \text{water received at the field inlet}$. The irrigation water available to the crop should be equal to the target deficit set by the selected management scenario. Therefore if the target deficit is met without water loss below the target depth or in runoff, then E_A would be 100%. Farmers with adequate recycling systems could experience some conveyance losses in recapturing runoff water and usually in the order of 15 %. Therefore maximum target of E_A during a recovery event would be 85 %. E_A can often be improved through changes to opportunity time.

5.3 Distribution uniformity

Distribution uniformity (DU) is a measure of how evenly water has been applied and is expressed as a percentage (%). Low distribution uniformity results in either part of a field being under-watered, or part being over-watered, in an attempt to apply sufficient water to the rest of the field. Calculating distribution uniformity for furrow-irrigated fields typically requires computer modelling to simulate an irrigation event. $DU = \text{average of the lowest 25 \% of infiltrated depths} / \text{average of all infiltrated depths}$. A target DU of >90 % would indicate that there is a ≤ 10 % difference between the averages of the lowest and highest quarters of infiltrated volumes along the field length. DU can often be improved through changes to flow rate and watering interval.

5.4 Requirement Efficiency

Requirement Efficiency (E_R) is a measure of how well the applied water has met or filled the target deficit. However, as measure on its own it is seldom useful, as it does not record losses nor does it describe the uniformity of the application in filling that deficit. The target deficit is the amount of water that the irrigation event aims to supply. Typically, surface irrigation events aim to refill the entire root zone to field capacity so that the interval between irrigation events is as long as possible. Whilst this strategy may be appropriate, production is compromised when an irrigation event is closely followed by a rainfall event, as the profile is already full and the rainfall may cause waterlogging. Furthermore, these large wetting/drying cycles make water-related agronomic management difficult. Another strategy is to aim to only partly refill the soil profile to improve the likelihood of capturing rainfall and allow manipulation of crop stress levels. This strategy of deficit irrigating results in more irrigation events per season, but a greater ability to capture rainfall and manage plant growth and reproduction. E_R is often improved by measuring the volume applied and the soil deficit and then by modifying time between irrigations (frequency of irrigation), inflow rate and TCO.

5.5 Frequency of application

The frequency of application is typically a balance between the amount of moisture in the soil, the likelihood of rain, crop development and the labour requirements for irrigation. Often irrigation intervals are stretched so that fewer irrigations are required during the season and hence less total labour will be required. However, stretching irrigation events can have a negative impact on the performance of surface irrigation systems, as a soil's properties (infiltration characteristics) vary with moisture content, and surface irrigation systems rely on the soil as the application system. Stretching irrigation events will decrease the rate at which irrigation water advances down the furrows (the empty profile takes longer to fill), subsequently affecting the uniformity of application, total application amount required to fill a certain deficit, water losses below the root zone and runoff.

5.6 Opportunity time

Opportunity time for infiltration consists of two phases the advance and the recession. As discussed before the advance phase is largely driven by the inflow rate, infiltration characteristics, field characteristics and the length of the irrigation. The recession phase is driven by the same parameters, but does not commence until after irrigation syphons have been stopped. It is this receding volume of water flowing down the field that satisfies the field water requirement that was not satisfied by the advance and which in some cases, allows the irrigator stop the irrigation inflow before the advance reaches the end of the field. The infiltration curve from SIRMOD analysis is a very useful tool when discussing opportunity time and determining the appropriate time to cut-off. The tool describes the time in which it takes to fill the deficit and the losses incurred for the period of inundation time. In many cases the deficit is satisfied very early in the irrigation and often extended run times serve little useful purpose in terms of filling the deficit, but simply generates losses.

5.7 Strategies

1. Compare total inflow and target deficit. An application in excess of the target deficit indicates potential run-off or deep drainage, or both.
2. Analyse soil moisture data to investigate wetting and extraction patterns and waterlogging. Sometimes it is possible to identify the occurrence of deep drainage using such data, but soils that remain saturated at depth may not show drainage, even when it occurs.
3. Investigate commercial analysis and modelling services
4. Modify infiltration characteristics (deficit), inflow rates and or TCO (<500 minutes) to achieve acceptable E_A (>85 %) and DU (>90 %).
5. Set irrigation management strategies to operate: a “no runoff” scenario, and a deficit irrigation strategy to capture a percentage of in-crop rainfall.

6. References

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Appendix 1

To Section: Soil and Chemical loss

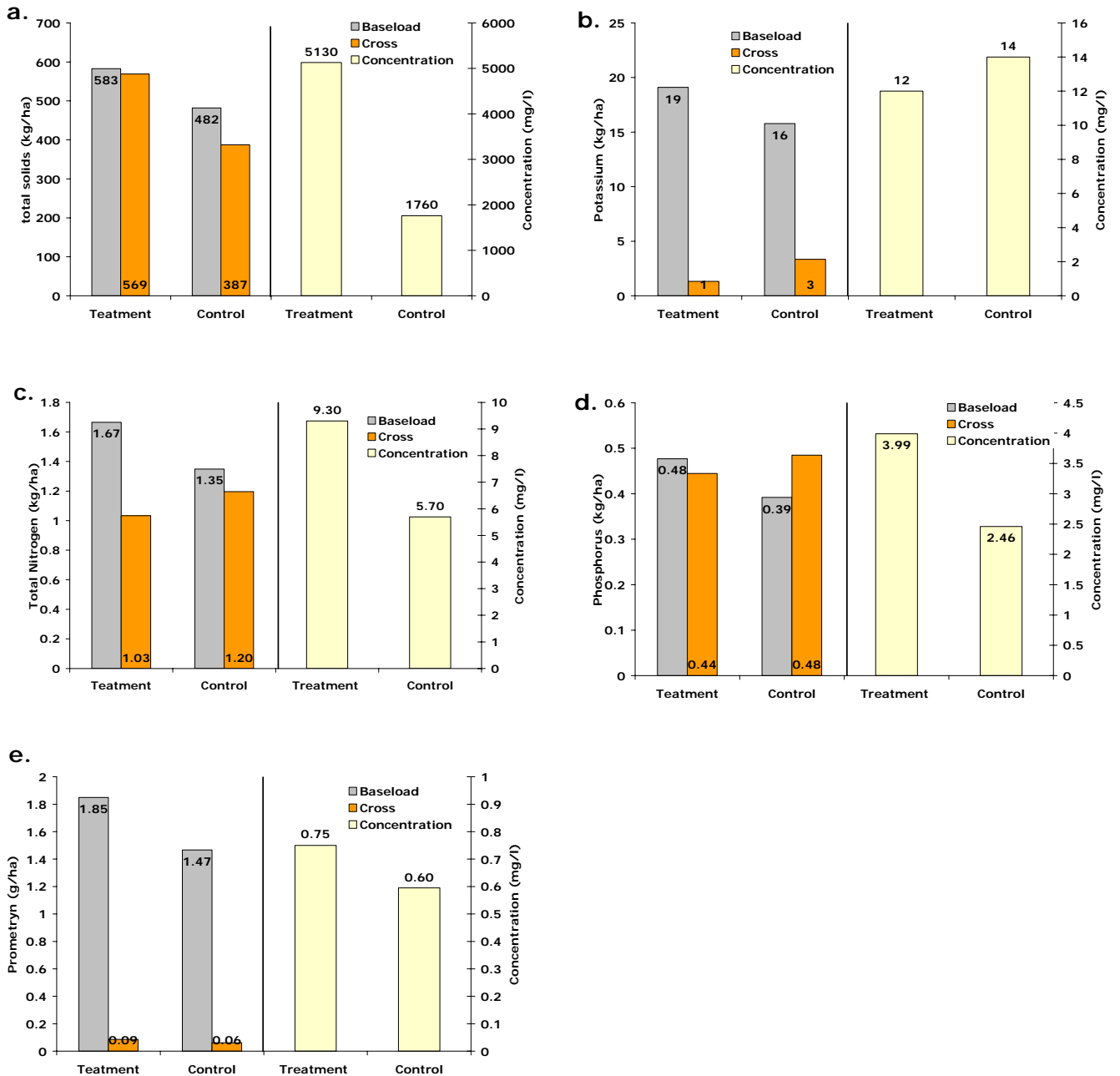


Figure 1. Total soil, chemical and nutrient loss from the fourth irrigation during the 2004/05 season. Figures a. total solids, b. Potassium, c. Nitrogen, d. Phosphorus, e. Prometryn, indicate concentration (mg/L) for each parameter, base load and net load in kg/ha.

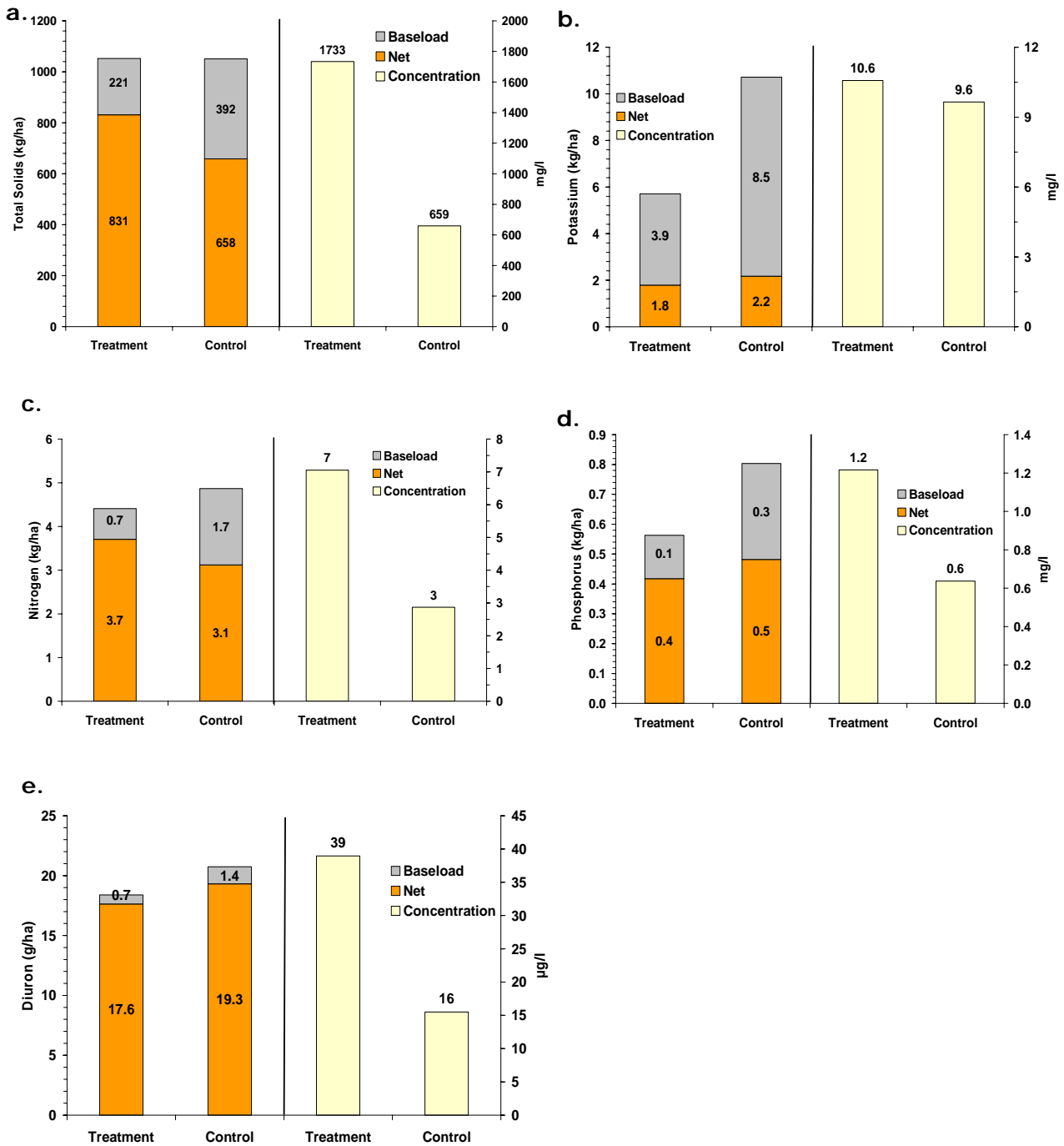


Figure 2. Total soil, chemical and nutrient loss from runoff during 2005/06 season irrigations. Figures a. Total solids, b. potassium, c. nitrogen, d. phosphorus, e. Diuron, indicate water concentration for each constituent, and base load plus net load in kg/ha leaving the field.

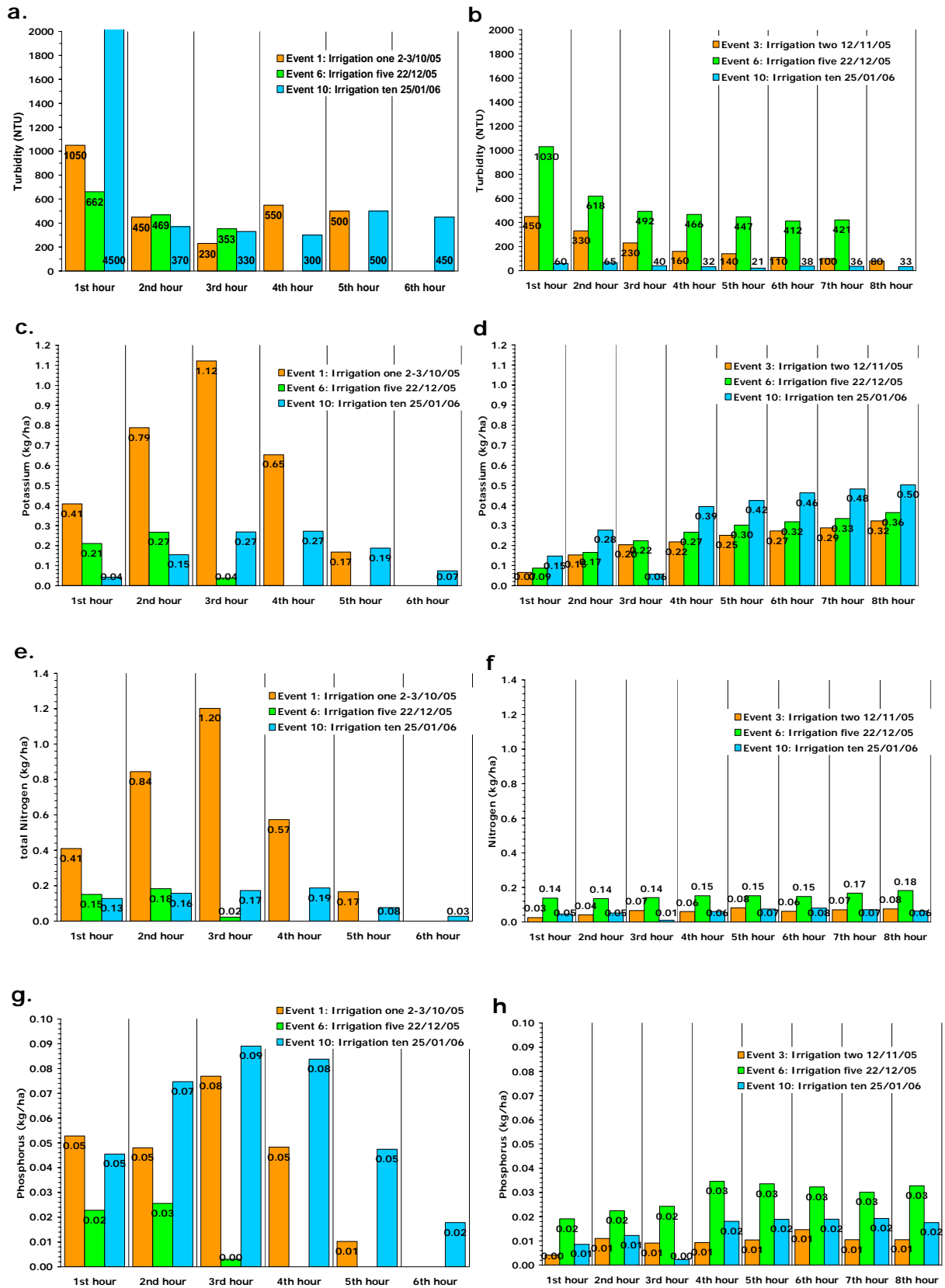


Figure 3. Time series water quality analysis for early, mid and late season irrigations events for the 2005/06 season. Left column figures (a. Turbidity, c. potassium, e. nitrogen, g. phosphorus) are for the treatment site and right column figures (b. Turbidity, d. potassium, f. nitrogen, h. phosphorus) for the control site.

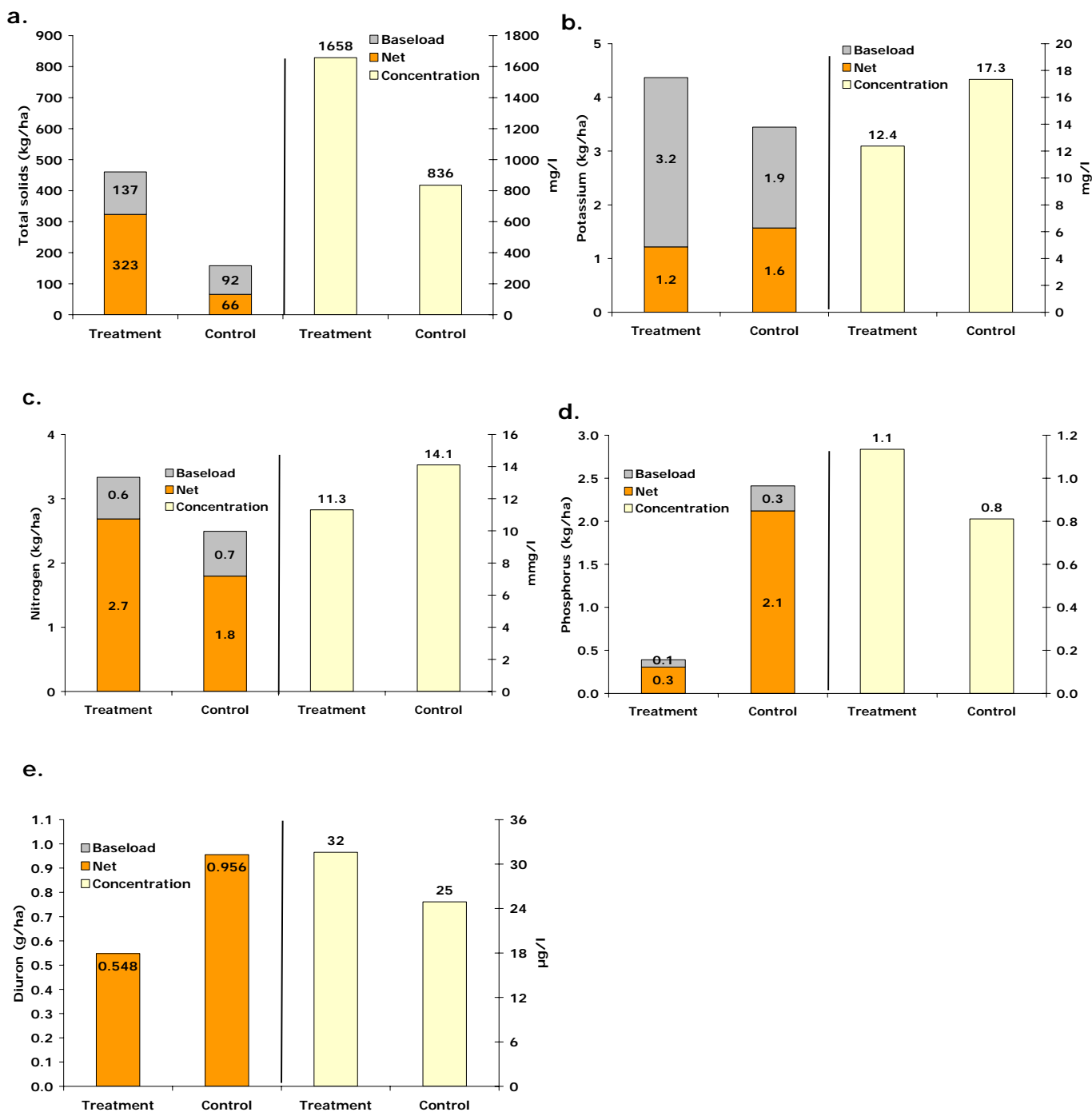


Figure 4. Total soil, chemical and nutrient loss from runoff during 2006/07 season irrigations. Figures a. Total solids, b. potassium, c. nitrogen, d. phosphorus, e. Diuron, indicate water concentration for each constituent and base load plus net load in kg/ha leaving the field.