Controlling deep drainage for improved WUE - and possible links with ground water movement

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Introduction

The financial and resource intensity of irrigated cropping necessitates that growers seek high returns from investments. This is economic and environmental pragmatism in times of ever increasing costs, irregular world markets and the spectre of both the unknown impacts of climate change and the increased usage of new sources of groundwater – commonly saline and/or sodic at source. Salinity in groundwaters and rootzones remains a continuing problem for irrigators, and growers are well aware that they have strong potential to ruin irrigation systems. The paradox, however, is that the potential problem of salinisation comes from the very water used to grow the crops that comprise the Australian irrigated cropping industry. The aim in this paper is to present “the good, the bad and the somewhat worrying” results from 8 years of research on deep drainage under cotton and how it links with possible change in practice, water use efficiency (WUE), salinisation and groundwater response.

Irrigation has the potential to both increase salt levels from low quality water as well as mobilise stored salts, leading to on- and off-site problems of salinisation. Deep drainage (DD) - water that passes beyond the root zone - leaches salts through the soil profile and deposits them either in the deeper rootzone, the vadose zone (that zone between the rootzone and the watertable) or in groundwater. If the DD causes water table rise to the rootzone with associated salts, then salt concentrations may preclude the growth of salt sensitive species. However, with low quality irrigation water, some DD is essential to leach salts from the rootzone.

A further complication is that irrigation practices designed to increase WUE may lead to a reduced leaching fraction (LF) *ie* the percentage of water (irrigation water and in-season rain) that bypasses the rootzone, and resultant increased soil salinity. Specifically, in Queensland there are over 500 overhead irrigation devices in operation, covering 43,000 ha; approximately 10% of the irrigated cropping area. The extent covered by this equipment reflects their attractiveness in saving water, particularly following a recent series of drought years. However, such systems apply less water compared to traditional furrow irrigation, and salt may accumulate in the root zone (Gunawardena et al 2010).

This project commenced in 2002 to monitor DD across a range of irrigated cropping lands in the upper Murray Darling basin. At its peak, there were 11 sites where lysimeters were installed (all but one in commercial, irrigated cotton fields) giving a total of 33 lysimeters with one near the head ditch, mid field and tail ditch in each field. This monitoring has continued but the project has widened to consider the related aspects of change in root zone salinity, whether DD (or other surface water events) are linked to groundwater rise, and most recently rootzone salinity change with new irrigation technologies aimed at improved WUE.

This paper will present results from the five main subject areas of the project: (i) deep drainage, (ii) WUE and soil salinity implications with a lateral move, (iii) DD leachate water quality, (iv) resistivity imaging showing deep “pools” of water and salt below irrigated fields and (v) links of surface irrigation with groundwater response.

(i) Deep drainage

The DD data over the life of the project are given in Table 1. Four important characteristics are apparent in these seasonal totals.

Firstly, there was a reduction in DD from the top of the field to the bottom, *ie* from head to tail ditch. This is evident for nine irrigation events (of 21 crop irrigation seasons, excluding the lateral at Boggabilla), as follows: Boggabilla furrow (2005-6), Goondiwindi (2003-4, 2004-5), Macalister (2002-3, 2005-6, 2008, 2008-9), St George (N) (2005-6) and St

George (S) (2003-4) (Table 1). The trend may be linked to a current water saving practice where irrigation siphons are stopped immediately when water reaches the tail ditch, so water inundation is far longer at the head than the tail.

Secondly, the largest DD values generally occurred in the 2002-3 and 2003-4 seasons. The five largest values recorded were 235, 196, 187, 176 and 175 mm from Goondiwindi head and mid (2002-3), Goondiwindi head (2003-4), Dirranbandi tail (2003-4) and Macalister head (2002-3) (Table 2). In 2003-4 DD was 27% of the water applied (in crop rain plus irrigation) at the Goondiwindi head and 15% at the Dirranbandi tail. These results seem related to either the use of large diameter siphons (75 mm at Goondiwindi) or lengthy periods of inundation on specific occasions. For example, the DD of 176 mm at Dirranbandi (tail) was linked to a continually blocked field exit drain at that site (in that season, subsequently repaired) and the 175 mm at Macalister (head) to the (intentional) flooding of the field prior to the commencement of drip irrigation for the remainder of the season. Overall, the proportion of seasons with DD >100 mm (=1 ML/ha) accounted for about 20% of seasons when there were DD events, *ie* 14 of 62 values. Though 1 ML/ha loss in one crop season may seem small in agronomic or water management terms, there are at least two ways of putting this value in context. Firstly, in terms of irrigating crops through the lateral move at the Boggabilla site, 1 ML/ha was sufficient to irrigate each of a chick pea and a sorghum crop (2008-9) and almost a full cotton crop in 2007-8 (Table 1). Secondly, the DD values of Table 1 can be expressed as the leaching fraction (LF) and these values compared to the leaching requirement (LR) required to maintain 100% yield of cotton (through effectively flushing out additional soil salts). This calculation[1] using a threshold soil EC = 7.7 dS/m (that ensures 100% cotton yield) and the average EC of the irrigation waters used at all the sites (though not Macalister as known to be above average salinity) gave an LR of 3.5%. Using this LR value, 57% of the seasons when there was a measured DD event (Table 1) were excessive, in terms of requirements to maintain the soil salinity level for cotton.

Thirdly, seasonal DD was absent or minor across all sites on a range of occasions. These included 8 seasonal DD totals between 1 and 10 mm (Table 1). An extreme example of variability was at the Macalister site, that recorded 175 mm of DD at the head in the 2002-3 season, and then only 5 mm DD at the same location in the 2003-4 season. The likely explanation is that the sorghum crop (of 2003-4) utilised almost all of the 720 mm (7.2 ML/ha) of water applied. Most evident are the very low values of DD recorded across many sites in the 2005-6 season, due to a combination of limited water supply and above average day and night air temperatures, recorded in that season. An absence of DD at the Dalby, Goondiwindi and Pampas sites from the 2005 season was associated with restricted availability of irrigation water at these sites in these drought years. Irrigations were infrequent, with small volumes, and were timed for maximum crop and economic benefit.

Fourthly, there are within-season trends in DD. An example of the cumulative daily DD data (from the 2004-5 season at Goondiwindi) is shown in Figure 1. There are "step" increases in cumulative DD for many of the irrigation events, and the largest of these mainly happened during the pre-irrigation, and at 1st and 2nd crop irrigations, after which there was almost no DD at head, mid or tail locations. At this site, DD for the first three irrigations in 2004-5 accounted for 50% of the total season DD, due apparently to a combination of farmer practice of shorter (time) and more frequent irrigations of more mature crops with greater transpiration and greater soil water deficits later in the season; leaving little water to bypass the rootzone as DD.

(ii) Improved WUE with a lateral move and salinity implications

Two adjacent fields near Boggabilla (NSW), one under traditional furrow irrigation the other with spray irrigation from a lateral move (LM), were selected to monitor DD and

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[1] $LR = EC_{iw} / (5EC_e – EC_{iw}) * 100$ where EC_{iw} is the electrical conductivity of the farm's irrigation water (dS/m) and EC_e is the threshold electrical conductivity of a saturation extract of soil (dS/m) for maximum cotton yield, gained from published tables.

root zone solute quality (in terms of salinity and sodicity) by installing six lysimeters at 1.5 m depth, 3 in each field. Soil in both fields was grey cracking clay.

The DD data under each irrigation practice at the Boggabilla site is given in Table 1. Since lysimeter installation, there has only been one DD event (31 mm) under the LM - linked to pre-season testing of the LM immediately above the head lysimeter, causing localised water ponding. There has been no further DD under the LM in 5 years. In contrast, in the two seasons when the furrow field was irrigated (2005-6 and 2007-8) there were DD of 105, 87 and 93 mm, and 19, 40 and 1 mm at the head, mid and tail locations, respectively (Table 1).

The total amounts of water applied in any one season also differed strongly between the furrow and LM fields. For various summer crops under the LM, water applications were: 2.7, 1.9, 1.3, 0.3 and 0.6 ML/ha in five seasons, compared to 6.3 and 4.5 ML/ha/season in the furrow field in the two years it was irrigated (2005-6 and 2007-8). This is a 57% and 71% reduction in water use with the LM in for the two respective seasons. Crop yield was similar in the two fields when cotton was grown (2005-6); approximately 8 bales/ha in each field. In 2007-8, yield data were not available for the cotton crop under LM, due to severe hail damage. The similar yields and differences in water supply in 2005-6 indicated greater irrigation water use efficiency (bales/ML) with the LM in this year.

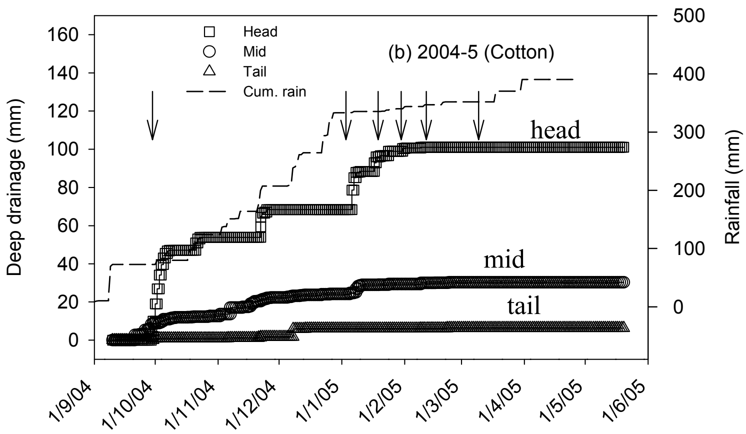

Figure 1. Cumulative deep drainage logged from the Goondiwindi site during the 2004-5 season. Cumulative rainfalls are also shown and the vertical arrows indicate irrigation events.

Soil salinity dynamics

To monitor the change in soil salts under the two different irrigation practices, soil cores were collected when the lysimeters were installed (September, 2005), then 48 and 56 months later for the LM and furrow sides, respectively. All cores were within a 2 m radius of each lysimeter and soil chemical properties measured on selected 0.1 m increments to 1.5 m.

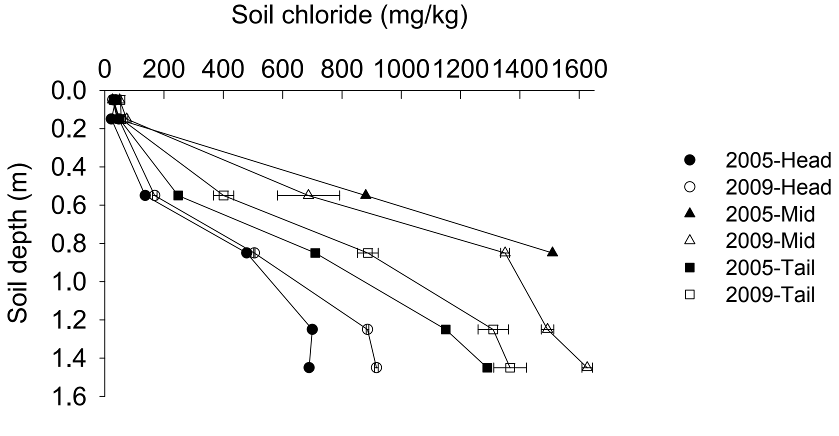

Figure 2. Changes in soil chloride to 1.5 m depth at head, mid and tail locations under the lateral move irrigator over four years at the Boggabilla site. The SD (±) for the 2009 sampling is shown.

Analysis showed both fields ranged in clay content from 40 – 50%, and there was no appreciable difference in soil EC profiles of the two adjacent sites when the initial samples were taken, all values being <1 dS/m throughout. Irrigation water quality at the Boggabilla site is very good (EC = 0.24 dS/m, SAR = 1.1, Cl = 18.5 mg/L) with water sourced from nearby Whalan creek, a tributary of the Macintyre river.

Under the LM, soil chloride increased at 72% of the sampled depths (where data was available in both years) in the 48 month period (Figure 2). The tail location had chloride increases below 0.5 m and at the head location below 1 m. Conversely, chloride decreased at the mid location for the two sampled depths below 0.5 m (Figure 2). The largest increase was at 1.5 m depth at the head location (227 mg/kg of chloride; a 25% increase). Considerable increase in chloride at deeper layers at head and tail locations showed a requirement of additional leaching fraction (*ie* DD) for long term salinity management. In the furrow irrigated field change in chloride was very small for the mid and tail, the only large increase in soil chloride being at the head location (Figure 3). Rationalisation of this result will require further sampling with more replication across more occasions to better determine site variability. With data presented in Table 1, the DD totals with furrow irrigation (over the two irrigation seasons) show little difference between head and mid locations (124 and 127 mm, respectively), hence do not aid rationalisation of change in Cl with time.

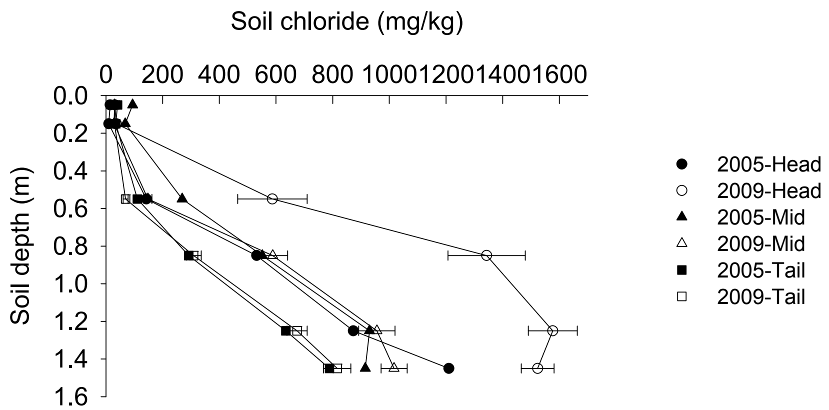

Figure 3. Changes in soil chloride to 1.5 m depth at head, mid and tail locations under the furrow irrigation over four years at the Boggabilla site. The SD (±) for the 2009 values is shown.

(iii) DD leachate water quality

The magnitude of EC of the leachates collected as DD at all sites was far greater than the EC of waters applied to each field (Figure 4). The largest increases were at the St George (N) and (S) sites, where there was a 40 and 60 fold increase, respectively (Figure 4). Furthermore, St George (N) and (S) had the largest soil EC values, being approximately 2.5 dS/m at 80-90 cm indicating various stages of salt transport processes among sites. The smallest increase in leachate EC compared to waters applied (3 fold) was at the Macalister site, where the irrigation water (principally bore water) was the poorest quality of all the lysimeter sites - with an EC of 4.2 dS/m, and soil EC of 1.5 dS/m at 80-90 cm depth (Figure 4). Furthermore, soil properties showed that EC was very low (<0.02 dS/m) throughout the sampled profile at both Dirranbandi and Pampas but 26 and 13 fold increases in EC were measured at these sites.

The variable salt transport processes associated with internal drainage are currently not fully rationalised from these data but may be related to bypass flow (through macropores), saturated hydraulic conductivity (mm/day) and exchangeable sodium percentage, specific to each site. These results, however, highlight the potential for adverse effects on water quality in the vadose zone beneath the crop rootzone and perhaps deeper into the water table, if the DD waters reach those depths.

Table 1. Deep drainage (DD, mm/season) measured in lysimeters at 3 positions in the field. The leaching fraction (%); *LF*= (DD) / (in crop rain + irrigation) * 100

Site	Crop	In crop rain (mm)	Irrigation (mm)	Season	Head		Mid		Tail	
					Vol.	*LF*	Vol.	*LF*	Vol.	*LF*
Boggabilla										
(a) furrow	Cotton	331	628	05/06	**105**	*11*	**87**	*9*	**92**	*10*
	Fallow	261	-	06/07	**0**	-	**0**	-	**0**	-
	Cotton	350	450	07/08	**19**	*2*	**40**	*5*	**1**	*0*
	Fallow	328	-	08/09	**0**	-	**0**	-	**0**	-
(b) lateral move	Cotton	331	270	05/06	**31**	*5*	**0**	-	**0**	-
	Cotton	261	196	06/07	**0**	-	**0**	-	**0**	-
	Cotton	350	131	07/08	**0**	-	**0**	-	**0**	-
	Chick pea	112	30	2008	**0**	-	**0**	-	**0**	-
	Sorghum	328	60	08/09	**0**		**0**		**0**	
Dalby	Cotton	302	465	04/05	**39**	*5*	**95**	*12*	**34**	*4*
	Soybean	449	400	05/06	**0**	-	**0**	-	**0**	-
	Sorghum**	274	100	06/07	**0**	-	**17**	*5*	**0**	-
	Cotton***	502	100	07/08	**0**	-	**0**	-	**0**	-
	Fallow	351		08/09	**0**	-	**0**	-	**0**	-
Dirranbandi	Cotton	260	926	03/04	**11**	*1*	**21**	*2*	**176**	*15*
	Cotton	251	600	05/06	**0**	-	**1**[c]	*0*	**6**	*1*
	Fallow	112	-	06/07	**0**	-	**0**	-	**0**	-
Goondiwindi	Maize	247	*	02/03	**187**	*	**196**	*	**24**	*
	Sorghum	400	462	03/04	**235**	*27*	**101**	*12*	**21**	*2*
	Cotton	317	563	04/05	**104**	*12*	**23**	*3*	**19**	*2*
	Sunflower	188	420	05/06	**0**	-	**1**	*<1*	**11**	*2*
	Fallow	210	-	06/07	**0**	-	**0**	-	**0**	-
	Fallow	383	-	07/08	**0**	-	**0**	-	**0**	-
	Mixed seed	211	*	2008	**0**	-	**0**	-	**0**	-
	Fallow	435	-	08/09	**0**	-	**0**	-	**0**	-
Macalister	Maize	297	*	02/03	**175**	*	**nf***	-	**51**	*
	Sorghum	364	720	03/04	**5**[c]	*<1*	**nf***	-	**33**	*3*
	Cotton	270	335	04/05	**41**	*7*	**101**	*17*	**0**	-

	Cotton	107	540	05/06	**12**	*2*	**10**	*2*	**0**	-
	Cotton	78	420	06/07	**31**	*6*	**26**	*5*	**0**	-
	Fallow	542	-	07/08	**31**	*6*	**26**	*5*	**0**	-
	Barley	278	*	2008	**41**	*	**6**	-	**0**	-
	Fallow	298	-	08/09	**13**	*4*	**0**	-	**0**	-
Pampas	Cotton	506	963	04/05	**71**	*5*	**106**	*7*	**62**	*4*
	Sorghum	432	-	05/06	**0**	-	**0**	-	**0**	-
	Fallow	209	-	06/07	**0**	-	**0**	-	**0**	-
	Sorghum	341	-	07/08	**0**	-	**0**	-	**0**	-
	Sorghum	390	-	08/09	**0**	-	**0**	-	**0**	-
St George (S)	Cotton	144	*	02/03	**14**	*	**68**	*	**37**	*
	Cotton	374	800	03/04	**104**	*9*	**91**	*8*	**18**	*2*
	Cotton	375	734	04/05	**40**	*4*	**92**	*8*	**50**	*7*
	Field pea	323	493	05/06	**5**[c]	*1*	**37**	*5*	**33**	*7*
	Cotton	125	700	06/07	**0**	-	**33**		**0**	-
	Fallow	532	-	07/08	**14**	*3*	**1**	*0*	**13**	*2*
	Wheat	133	*	2008	**0**	-	**0**	-	**0**	-
	Fallow	180	-	08/09	**0**	-	**0**	-	**0**	-
St George (N)	Wheat	75	*	2004	**24**	*	**55**	*	**1.6**	*
	Cotton	236	693	05/06	**27**	*3*	**22**	*2*	**0**	*0*

nf = non-operational lysimeter; replaced before the 2004-05 season
* Quantity of irrigation waters applied, not known.
** Sorghum irrigated to establish only (note the 17 mm of DD resulted from that one irrigation)
*** Cotton irrigated only once on 9 January 2008.

Note: lysimeters were installed at different sites in different years.

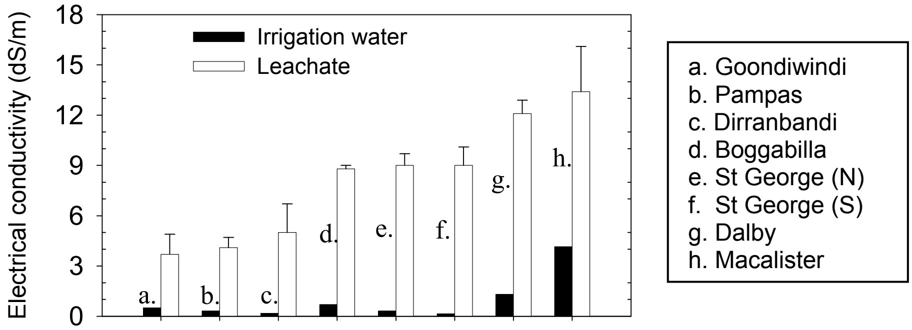

Figure 4. Water quality, in terms of electrical conductivity (dS/m), of both the irrigation waters applied at eight of the lysimeter sites and the deep drainage water collected (leachate). Data are the means of several irrigations seasons and collection times for each water source.

(iv) Resistivity imaging across a DD monitoring site

Geophysical surveying (using an ABEM SAS4000 Terrameter and LUND ES464) was used to make a 2-D pseudo-image. It is along an irrigation furrow (transect 480 m long, 21.5 m deep, width = X to Y metres) at the Pampas lysimeter site; a black self-mulching clay. Concurrently, soil samples were collected along the transect (to 6 m depth) to determine volumetric soil water content (cm^3/cm^3) and electrical conductivity (dS/m), chloride (mg/kg) and texture to assess the influence of salt and clay content on soil resistivity. The image was converted to conductivity (1/resistivity) with high conductivity (the blue colours in Figure 5) indicating high soil water content or salinity.

The top 1.5 m of soil was relatively dry as imaging occurred after harvesting sorghum grown without irrigation in the 2008-9 season (Table 1). The deep blue coloured zone (in the 1.5 to 6 metre layer) evident in Figure 5 shows that there is a very wet or salty zone throughout these soil depths in this irrigated field (supported by volumetric moisture sampling). The regolith, from 6 to 20 m, was less conductive (reds and purples), largely due to increasing sand content, and hence drier conditions. Some DD moving deep into the profile at 160 and 240 m along the transect indicated the possible migration of surface water downwards, or possibly capillary rise from shallow groundwater systems. In data not reported here, transects were imaged across naturally vegetated landscapes (as a reference) and out into irrigated fields. The soils under native vegetation were dry and had low conductivity, whereas the 1.5 m to 6 m of soil in all irrigated paddocks were found to be very wet, and in some instances saturated across large tracts of the landscape.

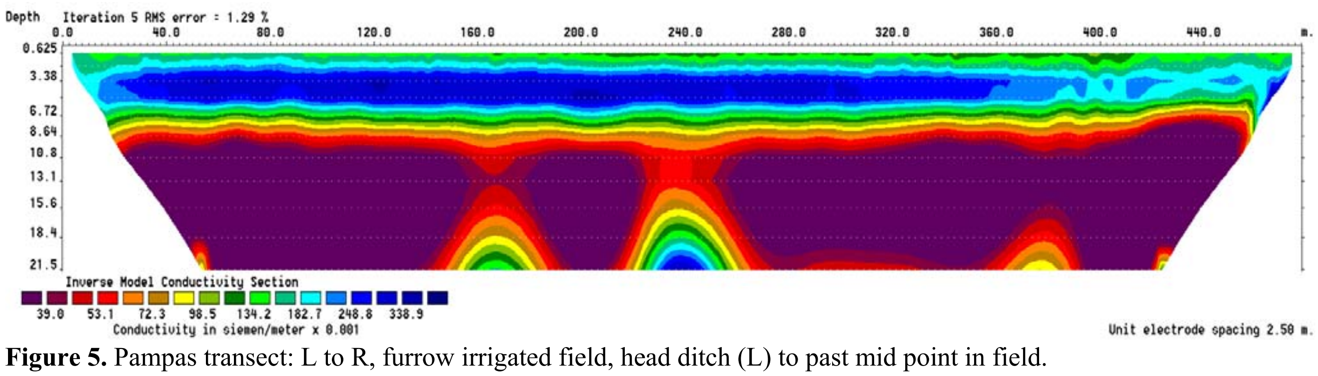

Figure 5. Pampas transect: L to R, furrow irrigated field, head ditch (L) to past mid point in field.
Taken from: Foley, J., Silburn, M., Greve, A. (in press). World Congress of Soil Science, August 2010, Brisbane: Resistivity imaging across native vegetation and irrigated Vertosols of the Condamine catchment – a snapshot of changing regolith water storage. pp. 4.

(v) Ground water response in the SIA, links with DD

Detailed investigation of the dynamics of groundwaters under the St George, southern irrigation area began in 2007. Analysis has been based on both the historic bore logs of the 16 "wet" (of 24 originally drilled) inspection boreholes (dating from 1972), as well as twice daily water level readings in the same boreholes that began in December 2007. Analysis of the historic water level data provides two main insights into changing groundwater levels in the area. Firstly, in the early to mid 1980s, the groundwater level in six of the inspection boreholes rapidly and dramatically rose towards the ground surface with a range of just under 3 metres to almost 19 metres. The water levels, in these six bores, has remained at these shallower levels since then, showing perhaps that the change in irrigation practices that commenced in the mid 1980s (especially the construction and filling of ring tanks) has continued to present time. The water levels, however, are all deeper than 5 metres below the ground surface. Secondly, the level of water and its dynamic in the inspection boreholes does not particularly illustrate the presence of a broad groundwater mound under the irrigation area. Rather, there appears to be development of more localised groundwater mounds, most probably reflecting zones of locally preferential connectivity of the land surface with the upper aquifer, from channel and on-farm storages leakage, as well as from recent heavy rains and local flooding. Importantly, the historic and recent data logs show that groundwater levels have not approached the 2 m below-ground-level mark that is commonly regarded viewed as posing a risk for soil salinisation *via* capillary rise of groundwater. The study continues.

Conclusions

Deep drainage occurs in irrigated fields of the UMDB, though quantities >2 ML/ha/season were rare. More than 1 ML/ha/season occurred in 20% of measured irrigated events; considered quite a large value in terms of both the potential of achieving good crop production with about 1 ML with more water use efficient apparatus (*eg* lateral move) as well as in over-achieving the leaching requirement of these soils to maintain salinity levels for continued 100% cotton yield potential. Water scarcity in drought years, leading to restricted irrigations, dramatically reduced DD losses and there were many instances with no measured DD in those years. DD has been shown to be a "start of irrigation season" phenomenon, so any reduction in water applied in the pre- or early crop irrigations has the potential to dramatically reduce DD. Perhaps a "quick" pre-irrigation could be used to seal cracks, to lessen DD at the 1st crop irrigation. The LM most certainly improved WUE (up to 71% reduction in water applied with equivalent yield) but the almost total lack of DD seems to be leading to salt accumulation in the rootzone. However, it is stressed that longer monitoring is required to understand the dynamics of salt accumulation and export associated with this type of irrigation practice.

DD leachates have been found to be very saline relative to the quality of the irrigation waters applied, showing the great potential of salts moving to rivers and groundwaters. This shows the quandary that if DD is increased to keep the rootzone salt-free then there is a risk of off-site pollution through salty DD leachates. A balance of over and under irrigating is required.

The resistivity data suggests that the DD from long term irrigation has filled the top 1.5 to 6 metres of the vadose zone; and created a much wetter water regime to that under native vegetation. Again, this illustrates "wasted" water, not utilised for economic return and potentially leaking to groundwaters. Groundwater in the St George irrigation area rose dramatically in isolated spots at the time when ring tanks were introduced, seemingly linked to some (as yet) ill-defined connectivity between surface water and aquifers. The input from irrigation waters (field, storage and channels) has maintained these water levels, gained in the mid 1980s with further small, steady rises. The shallowest water level is 5 metres below ground level - well below the level deemed of concern for short-term salinisation. Again, monitoring should be continued, particularly to better comprehend the drivers of rising water tables.

Reference

Gunawardena TA, McGarry D, Gardner EA (2010) Will increased Water Use Efficiency lead to salt accumulation in the root zone? A comparison of adjacent lateral move and furrow irrigation. In *"Proceedings of the Irrigation Australia 2010 National conference 8 -10 June"* Sydney, Australia. pp 71-72.