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Quantifying deep drainage in an irrigated cotton landscape

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EXECUTIVE SUMMARY

Deep drainage below the root zone is still the least understood component of the water balance, especially in cracking clay soils. It represents a waste of a valuable resource and can leach nitrogen out of the root zone. It has the potential to cause watertables to rise, with the accompanying risk of salinity. Drainage can move contaminants, such as salt and agrochemicals, into the groundwater.

The lysimeter facility at the Australian Cotton Research Institute, near Narrabri NSW, was used to study drainage, its contaminants and its interaction with groundwater in a heavy clay soil under a furrow-irrigated cotton – wheat rotation from 2006 to 2011.

Drainage during the cotton seasons varied from 0 – 74 mm, under wheat it was negligible and under fallow it was 23 mm. Drainage occurred in two forms: matrix drainage and by-pass drainage. The former occurs when the water storage capacity of the soil is filled due to prolonged rainy periods with any extra water becoming drainage. Drainage rates are not high (<0.5 mm/day) but can continue for periods of a month.

By-pass drainage occurs after furrow irrigation when water flows rapidly down macropores and by-passes the matrix of the subsoil. Peak drainage rates are reached 25 hours after irrigation and can reach more than 3 mm/day. The rate then declines exponentially over a week to about 0.5 mm/day. The amount of by-pass drainage appears to be controlled by the soil water deficit in the upper metre of soil. Drainage increases as the 0 – 0.5 m layer becomes drier, possibly due to greater cracking. However, larger deficits in the 0.5 – 1.0 m layer decrease drainage and appear important in mitigating by-pass drainage.

The risk of by-pass drainage is greatest when irrigation is necessary early in the cotton season, when the crop is too small to create a subsoil deficit between irrigations, especially if the subsoil was already wet before sowing.

The risk of matrix drainage can be minimized by managing both the rotation and irrigation scheduling to ensure there is sufficient deficit to accommodate likely inputs of water and irrigation at any time of year. Nevertheless there will always be times of above average rainfall when the profile is filled to capacity and drainage occurs.

However, some drainage is necessary to leach salts from the irrigation water that accumulate in the root zone. The electrical conductivity (EC) of matrix drainage is greater than by-pass drainage, suggesting matrix drainage is more efficient at leaching salt.

In addition to salt, drainage leaches nitrogen from the topsoil. During the 2008/09 cotton season approximately 9.5 kg N/ha – equivalent to 6% of that applied as fertilizer – was lost in drainage.

Seasonal drainage from the root zone appears to recharge the watertable at 16 m depth within weeks, although this result is still tentative. There is continuous downwards leakage of salty water from the upper, watertable aquifer into the lower confined aquifer, from which water is extracted for a variety of uses. This leakage is exacerbated by pumping from the lower aquifer.

The lysimeter was also used to test less expensive methods of estimating drainage. A barrel lysimeter installed near the lysimeter facility overestimated drainage, whereas the chloride mass balance method underestimated drainage.

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1. BACKGROUND

Deep drainage is water that travels downwards out of the soil profile beyond a depth at which it can be extracted by plant roots. It is generally a small but important part of the soil water balance, which can be expressed as:

$$P + I = RO + ET + D + \Delta S$$

where:

P	Precipitation
I	Irrigation
RO	Net runoff (*i.e.* runoff less run on)
ET	Evapotranspiration (water use by plants plus evaporation from the soil surface)
D	Deep drainage
ΔS	Change in soil water content (positive for increase).

The water balance simply expresses that inputs of water into the soil (rainfall and irrigation) must equal outputs (runoff, evapotranspiration and deep drainage) plus any change in water content.

In irrigated agriculture some deep drainage is essential in order to prevent the accumulation of salt dissolved in irrigation water and left behind in the soil as the crop uses the water. In some regions it is necessary to deliberately add a 'leaching fraction' to the amount of irrigation applied to prevent salinisation (Richards 1954). However, excessive deep drainage can also have negative effects:

- Excessive drainage is a waste of irrigation resources.
- Drainage can also waste plant nutrients, especially nitrogen, by leaching them from the root zone.
- The leaching of plant nutrients and other agrochemicals by deep drainage can lead to contamination of groundwater.
- In arid and semi-arid climates there is usually little deep drainage under native vegetation, since native ecosystems have adapted to use most of the annual rainfall. When land is cleared for agriculture, deep drainage generally increases and changes the hydrology of the landscape causing watertables to rise. This is particularly the case when extra water is added in the form of irrigation. The rise in the watertable can cause waterlogging in low

parts of the landscape. If the groundwater is saline, the waterlogging is accompanied by salinity.

- In addition, the lack of deep drainage under native vegetation in arid and semi-arid climates has caused salts, from rainfall and/or mineral weathering, to accumulate below the root zone over long periods of time. The extra drainage associated with agriculture and irrigation can mobilise these salts. On sloping land, the mobilisation of salt can cause localised salinity outbreaks where the extra drainage seeps from the surface on lower slopes. In flatter areas, the salt is added to the groundwater and can cause more widespread salinity, when the watertable rises near the surface.

- Rising watertables due to increases in recharge can also change interactions between surface water and groundwater causing, for example, discharge of saline groundwater into rivers.

Since the late 1990s there has been an interest in drainage from heavy cracking clays – Vertosols – under irrigated cotton. Up to that point it had been widely believed within the irrigation industry that there was no leakage under such soils due to their high clay contents (Hearn 1998). Various lines of evidence, including a study of deep drainage under dryland farming systems on the very heavy clays of the Liverpool Plains of northern NSW (Ringrose-Voase *et al.* 2003), estimated non-negligible drainage under such soils. Silburn and Montgomery (2004) reviewed research on deep drainage under furrow irrigation finding values of 50 – 300 mm per season.

Understanding and quantifying the water balance are essential for the efficient management of irrigation and for ensuring sustainable management of soil and groundwater resources. However, drainage is the most elusive component of the water balance to measure, and most studies have used indirect methods to estimate it. The methods most commonly used to estimate drainage in irrigated agriculture in Australia include the following:

- Drainage can be estimated by measuring or calculating other components of the water balance (e.g. Ringrose-Voase *et al.* 2003). The risk is that errors in measurement of the other parts of the water balance tend to accumulate in the drainage estimate and can be of the same order of magnitude as the drainage term because drainage is generally small relative to other components of the water balance.

- The chloride mass balance technique can be used to estimate drainage on the basis of the build up of chloride in the soil profile based on its content in applied irrigation water and rainfall and the amounts of irrigation and rainfall.

- The barrel lysimeter developed by Queensland Department of Environment and Resource Management (Gunawardena *et al.* 2011) estimates drainage using a device to capture the drainage at 1.5 m depth. The device consists of a column of soil (0.3 m diameter), which is encased across its base and lowest 0.35 m of its length. A collection mechanism consisting of silica flour and ceramic candles is located at the bottom of the soil column. The column is then reinstalled in the ground and a suction applied to the collection mechanism to bring any drainage to the surface.

All of these methods have weaknesses in how they measure or estimate drainage. In 2003, CRDC project CRC47C “Quantifying deep drainage using lysimetry” started with the objective of providing direct, accurate measurements of deep drainage under irrigated cotton. During the project an equilibrium tension lysimeter was constructed under a cotton-wheat plot at the Australian Cotton Research Institute (ACRI) near Narrabri that enabled accurate measurement of deep drainage (Ringrose-Voase and Nadelko, 2006). The facility also measures other components of the water balance.

The facility acts as a benchmark against which to test less expensive methods of estimating drainage. Drainage is estimated at the site using:

- The chloride mass balance method (in collaboration with N. Hulugalle, NSW Department of Industry and Investment),

- Barrel lysimeter (in collaboration with D McGarry, Queensland Department of Environment and Resource Management).

Other projects that made use of the facility have included:

- Developing electrical resistivity imaging as a tool for quantifying soil water storage in the profile over long transects so that its spatial variability is captured (I. Akworth and B. Kelly, University of NSW);

- Investigating the use of 3D resistivity tomography to measure small scale soil moisture variation and subsurface crack detection (A. Greve, University of NSW).

- Field experiments to develop a simple and rapid method for the determination of deep drainage and leaching requirement. (E. Trainer, University of Sydney).

- A National Program for Sustainable Irrigation project run by R. Stirzaker investigating the use of “LongStop” wetting front detectors to show irrigators when drainage occurs and thus provide an essential feedback loop to allow them to manage irrigation better.

If methods such as these prove able to provide estimates within reasonable error margins and without bias, there is potential for using them to a) help irrigators better manage water and b) researchers to widely instrument a landscape to provide data with which to verify catchment scale models. Currently measurements tend to be either for the whole of the catchment (e.g. gauging stations) to verify catchment outputs or a few, intensively monitored sites to verify point scale aspects of models such as crop water use. There is a need for verification data from many more sites within a landscape, some of which are located where water fluxes might converge or diverge, to check model links between point scale processes - that relate to land management and can be manipulated by land managers - with catchment outputs.

It has proved difficult to match estimates of drainage from the rootzone with estimates of groundwater recharge. Determining the fate of drainage and how much of it reaches groundwater and after what delay were identified as priorities at a Cotton CRC Deep Drainage Workshop held in Narrabri in November 2003 (Silburn *et al.* 2004) as well as in a report by Kelly *et al.* (2007) entitled "Groundwater Knowledge and Gaps in the Namoi Catchment Management Area." The existence of the lysimeter to measure drainage provides an opportunity to investigate links with groundwater by monitoring piezometers installed nearby.

In addition, the lysimeter facility provides an opportunity to examine whether drainage from cotton is contaminated by salts, fertilizers or other agrochemicals. To date most research on this topic has either examined groundwater contamination, where there can be considerable delay between leaving the root zone and arrival at the groundwater - making interpretation more difficult - or examined drainage contamination using suction cups which do not necessarily sample water that is representative of that draining from the root zone. Examination of the chemistry of drainage can also provide insights into fundamental soil processes associated with irrigated agriculture such as changes to soil chemistry, in particular to exchangeable cations (sodium, potassium, calcium and magnesium) and losses of carbon.

2. OBJECTIVES

The objectives of the project were :

- To quantify the water balance, in particular deep drainage, in an irrigated cotton landscape, including different management practices and soils.
- To improve process understanding and models of the water balance in heavy clay soils, in particular with regard to 'by-pass flow'.
- To investigate links between drainage from the root zone and groundwater.
- To assess and compare different technologies to measure soil water that could be tactically used by irrigators to improve water management and lessen drainage.

The outcomes desired from the project were:

- Identification of situations where water management most needs improvement
- Potential strategies to reduce drainage
- Improved understanding of mechanisms by which drainage travels to groundwater

3. METHODS

3.1 Location and soil properties

The ACRI lysimeter facility near Narrabri in northern New South Wales was used to measure deep drainage and other components of the water balance in a cotton-wheat plot in paddock C1 (30° 11.53' South, 149° 36.31' East).

The soil at the site is fully described in Ringrose-Voase and Nadelko (2006). In summary, it is a Haplic, Self-mulching, Grey Vertosol (Isbell, 1996), which is grey to about 1.2 m depth and brown below this. Above 1.2 m depth the soil is 60% clay (<2 μm), 14% silt (2-20 μm) and 25% sand (20-2000 μm). Below 1.2 m, the clay content decreases to 50% by 2 m depth with corresponding increases in silt and sand to 20% and 30%, respectively. The exchangeable sodium percentage (ESP) increases with depth from <1% at the surface to 6-7% below a depth of 1.5 m, meaning the soil below 1.5 m is mildly sodic. Measurements of hydraulic conductivity indicated there is a compacted layer at about 0.3-0.7 m depth. The greatest hydraulic conductivities are found in the subsoil below 1.2 m, despite the bulk density also being greatest below this depth..

3.2 ACRI lysimeter facility

3.2.1 Drainage and soil hydraulic potential

The ACRI variable tension lysimeter facility was used for accurate, high frequency measurement of drainage. It achieves accuracy by applying a vacuum to the lysimeter trays that is equal to the hydraulic potential of the surrounding soil. This aims to ensure that the hydraulic gradient above the tray – which drives the magnitude of the drainage flux – is the same as that in the surrounding soil. Without the vacuum, water could only enter the tray when sufficient has collected above the tray to reach saturation. This would result in the soil above the tray being wetter than the surrounding soil, so some drainage would be 'pulled' sideways and not be collected in the trays. In addition, it would interfere with the timing of collection and impact measurements of the inorganic chemistry of the drainage.

The lysimeter facility follows a design by Brye *et al.* (1999) and modified by Foley *et al.* (2003) and Pegler *et al.* (2003). It is fully described in Ringrose-Voase and Nadelko (2006).

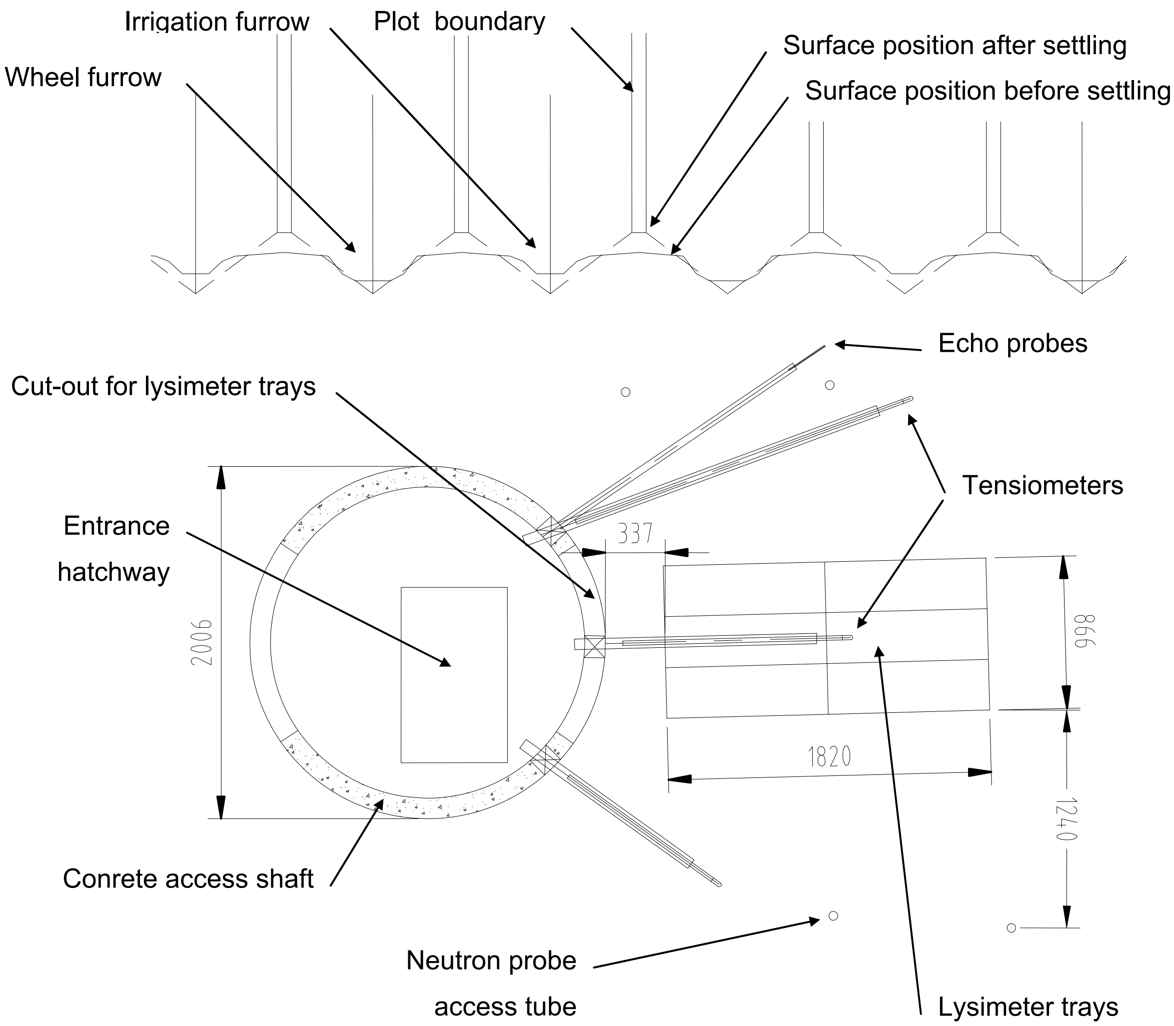


Figure 1. Plan view of lysimeter trays, access shaft, and other instruments. Dimensions in millimetres.

The lysimeter facility consists of a cylindrical access shaft made of reinforced concrete extending from about 0.5 to 4.0 m below the soil surface. A metal entrance hatchway is positioned so as not to interfere with the flow of irrigation water in the furrows. The lysimeter itself consist of six trays (each with horizontal cross section 910 × 286 mm) installed in a 2 × 3 array (total horizontal cross section 1820 × 866 mm, including soil shoring) giving a total collection area of 1.58 m^2 (Figure 1). The trays were installed at 2.1 m depth by tunnelling horizontally through a window cut in the wall of the access shaft (Figure 2). Thus the soil overlying the collection trays is undisturbed. The ceiling of the tunnel was prepared before the trays were inserted by applying epoxy resin and fibreglass to the ceiling, allowing it to cure and then peeling away the surface. This removed the smearing created during tunnelling and left a natural soil surface. The 0.35 m of tunnel between the trays and the concrete was back-filled with soil from the same layer that had been air-dried, crushed to

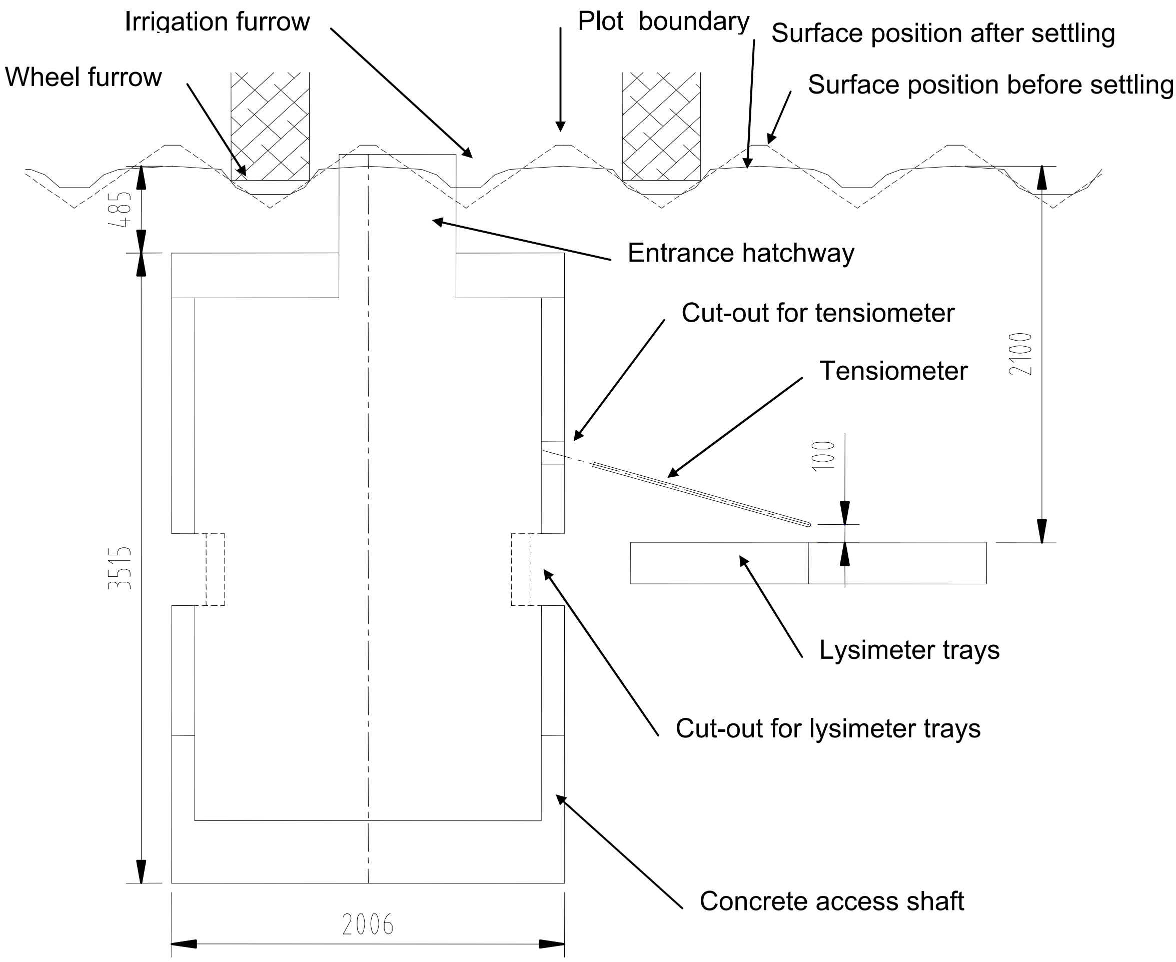


Figure 2. Vertical cross-section through the centre of the access shaft at 90° to the furrows. Dimensions in millimetres.

<10 mm and packed into the void to a bulk density of 1.24 Mg/m^3 (compared to original bulk density of 1.65 Mg/m^3).

The lysimeter trays are stainless steel boxes (910 × 286 mm cross section, 300 mm height). The upper surface consists of sintered, stainless steel filter that is 1 mm thick, has a nominal pore diameter of 0.2 μm and is very transmissive to water. Once the filter is saturated, the tray can hold a vacuum of -28 kPa before air-entry occurs. The floor of the tray slopes to one corner where there is a drain. There is also a vacuum port into the tray. Each tray is mounted on two air jacks that allow it to be pressed upwards to ensure good contact with the ceiling is maintained.

The gap between the upper surface of the trays and the soil was filled with a contact material of silica flour that had been graded by sedimentation to remove particles finer than 15 μm, which might block the steel filter. A 0.5 μm fibreglass filter was also placed between the upper tray surface and the contact material to help prevent blockage of the steel filter by silica particles. The hydraulic properties of the contact material ensure that it has sufficient conductivity to handle the likely drainage fluxes at any water potential between saturation and -28 kPa.

The drain from each tray is connected by Teflon® tubing to its own collection tank inside the access shaft, so that any drainage entering the tray flows by gravity into the tank. The tanks hang from load cells to allow their weight to be individually logged. There is also a vacuum port in each tank. Isolation valves on the vacuum and drain connections into the tanks allow sample collection from a tap at the bottom of each tank while maintaining uninterrupted operation of the lysimeter

The vacuum ports in the lysimeter trays and collection tanks are connected to a common manifold to which are fitted two needle valve-regulated solenoid valves. One solenoid value is connected to a vacuum supply reservoir mounted in the access shaft. The reservoir is kept at between -45 and -50 kPa by an automated vacuum pump. The second solenoid valve vents to atmosphere.

Two vertical arrays of tensiometers are installed 1 m either side of the trays, one under an irrigation furrow and the other under a wheel furrow (Figure 1). The depths of the tensiometers are 0.9, 1.2, 1.5, 1.8 and 2.1 m. A single tensiometer is installed at 1.95 m depth immediately above the centre of the trays. The latter is used to check that the hydraulic potential above the trays is the same as that at the same depth in the surrounding soil, obtained by averaging tensiometers at 1.8 and 2.1 m depth.

A data logger in the access shaft reads the tensiometers and the weights of the collection tanks every 15 minutes. Apart from storing the data, it also calculates the mean hydraulic potential at tray depth using the two tensiometers at 2.1 m. This value becomes the target potential for the next 15 minutes. During those 15 minutes, the data logger monitors vacuum inside the lysimeter trays and collection tanks at one second intervals using a pressure transducer. If the vacuum deviates from the current target potential by more than 0.1 kPa, the data logger opens either the vacuum supply solenoid or the atmospheric vent solenoid to adjust the system vacuum. If the mean hydraulic potential in the soil is less than -25 kPa, the data logger limits the target potential to -25 kPa to prevent air-entry through the filter.

The facility is powered by a 56 Ah rechargeable battery and 20 W solar panel, and has telemetry via the mobile phone network. Additional failsafe equipment protects the facility against lightning surges, galvanic corrosion, flooding of the access shaft and overfilling of the collection tanks. Confined-space protocols are followed when entering the access shaft including continuous atmospheric monitoring for oxygen, carbon monoxide, hydrogen sulphide and flammable gases, and stand-by personnel.

3.2.2 Soil water content

Four 3 m deep neutron moisture meter access tubes are installed 1.2 m from the trays, aligned with the hills. These are used to measure soil moisture content at 0.2, 0.4, 0.6, 0.9, 1.2, 1.5, 1.8 and 2.1 m depth. Additionally the water content for 0-0.05 m depth was measured gravimetrically and converted to volumetric content based on an established empirical relationship. The 9 depth intervals used to convert the volumetric soil water contents to millimetres of water were 50, 250, 200, 250, 300, 300, 300, 300 and 300 mm. A shape factor of 0.753 was applied to the second layer to allow for the furrow shape, giving this layer an effective depth of 188 mm.

Measurements are usually made the day before an irrigation and two days after. Additional measurements are made after heavy rain and at intervals of not more than 1 week during the irrigation season and 2 weeks at other times. A single vertical array of Echo capacitance probes was installed at the same depths as the tensiometers to enable continuous monitoring of water content. However, they did not work satisfactorily because difficulties remotely installing them in undisturbed, dense subsoil resulted in inconsistent contact between the instruments and the soil.

3.2.3 Inorganic chemistry of drainage water

The collection tanks are emptied before each irrigation during the irrigation season if sufficient volume is present for analysis. At other times they are emptied as necessary. Temperature corrected electrical conductivity (EC) and pH of the leachate is measured using portable meters. Other components of the inorganic chemistry were analysed in the laboratory, including NO_3^-, Cl^-, K^+, Na^+, Ca^{2+} and Mg^{2+}. Chloride analysis used the method of Beatty and Loveday (1974). Methods L1B, L2B and L4B of Rayment and Higginson (1992) were used for analysis of calcium, magnesium and sodium, respectively, but with strontium chloride substituted for lanthanum chloride. Nitrate analysis used the method of Page (1982).

3.2.4 Groundwater heads

Two piezometers, P1 and P2, were installed 5 m and 10 m up furrow from the lysimeter, respectively. The piezometer construction consisted of 80 mm PVC casings installed into 200 mm diameter bores drilled with a mud rotary rig. The piezometers were each fitted with 1 m of machine-slotted PVC screens and a fine washed gravel pack. Casings were sealed with bentonite and cement-grout at the ground surface, across aquitards and above screens. Piezometer P1 is screened at 20 m below ground surface (bgs), near the bottom of the water table aquifer, and P2 is screened at 34 m bgs in the next lower, confined aquifer.

The groundwater head in each piezometer is recorded hourly using submersible, temperature-corrected level loggers. The level logger data is downloaded via direct–read cables connected to the loggers through underground conduits from the buried wellheads. The conduits also serve to vent the piezometers to atmosphere. Barometric pressure is also recorded hourly using a sensor monitored by the lysimeter data logger in the access shaft. The barometric data is used to correct the level logger absolute pressure head data. The piezometer and level logger elevations are referenced relative to the local ground surface topographic elevation of 200.0 m.

3.2.5 Weather

Daily rainfall is measured by a gauge next to the lysimeter and other meteorological parameters by the ACRI weather station located about 2 km from the lysimeter.

3.2.6 Alternative methods to measure drainage

Since one objective of the lysimeter facility is to test alternative, cheaper methods of estimating drainage, two other methods are used in the vicinity of the lysimeter.

Chloride mass balance determinations are used to estimate seasonal drainage by measuring chloride content of replicate soil cores taken at the start and end of the season (N. Hulugalle and T. Weaver, NSW DII).

Four barrel lysimeters (Gunawardena *et al.* 2011) were installed in the same plot as the lysimeter – one 25 m down-furrow from the head ditch, one 3.5 m up-furrow from the tension lysimeter, one 3.5 m down-furrow from the lysimeter and one 25 m up-furrow from the tail ditch. These are much less expensive to install but apply a constant potential to the base of the lysimeter barrels. In addition, their installation requires considerably more soil disturbance above the lysimeter than the main lysimeter. Gunawardena *et al.* (2011) installed barrel lysimeters at 1.5 m depth at other sites, but at the ACRI lysimeter facility they were installed at 2.1 m depth so that the drainage they collected could be better compared to that measured by the variable tension lysimeter, which is also installed at 2.1 m depth. The two barrel lysimeters close to the tension lysimeter were intended for comparison, but one of them has, unfortunately, never operated since installation in May 2005.

3.3 Operations

The lysimeter facility has collected data since the 2006/07 cotton season as shown in Table 1. Data was collected during three cotton crops, one wheat crop and one fallow period. During most of the first cotton crop, the measurement of drainage, reading the tensiometers and setting the vacuum in the lysimeter trays was performed manually while the electronic equipment was being connected to the data logger and the latter was being programmed. The automatic measurement and vacuum regulation system commenced in March 2007.

Table 1: Cropping and data collection at the ACRI lysimeter facility.

Dates			Crop	Data collection
Oct 2006	-	May 2007	Cotton	Manual (to Feb 2007) Automatic (from Mar 2007)
May 2007	-	Dec 2007	Wheat	-
Dec 2007	-	Oct 2008	Fallow	-
Oct 2008	-	May 2009	Cotton	Automatic
May 2009	-	Dec 2009	Wheat	Automatic
Dec 2009	-	Oct 2010	Fallow	Automatic
Oct 2010	-	June 2011	Cotton	Automatic

Data was not collected during the 2007 wheat crop or 2008 fallow period because the lysimeter was out of operation in order to test and redesign the filters above the trays. The filters had been identified as a potential blockage due to their inadequate re-wetting properties. This required uninstalling the trays and testing both the silica flour contact material and the filter pack above the trays. The original filter pack consisted of three filters – from bottom to top: a 0.5 μm fibreglass filter, a 1 μm polypropylene needlefelt filter and a 5 μm polypropylene needlefelt filter. Testing before the original installation showed these filters to be extremely porous and very conductive when saturated. However, the two polypropylene filters were found to be significantly less hydrophilic than either stainless steel or quartz silica. Once installed they were sandwiched between these two materials which do not release water until much greater suctions than the needlefelt filters. The effect was that, as the soil dried and the suction in the trays was increased, the filters dried beyond their air-entry suction and de-saturated. When the soil was re-wet, the contact material rewetted before the filters. This resulted in the air within the polypropylene filters being trapped between the re-wet contact material and continuously saturated porous steel, impeding flow into the trays. The trays were therefore reinstalled with only the 0.5 μm fibreglass filter. The lysimeter trays were brought back into full operation in October 2008.

The piezometers near the lysimeter and associated instrumentation to log groundwater levels became operational in March 2008 during the 2008 fallow period.

4. RESULTS

4.1 Drainage

4.1.1 Seasonal summary

Table 2 to Table 5 summarize for each season the drainage measured by the lysimeter and its EC, together with inputs of rainfall and irrigation. Also shown are estimates of drainage obtained by barrel lysimeter and the chloride mass balance approach (discussed later).

Irrigation is difficult to measure when applied by furrow. In this case it was estimated as:

the amount of water that infiltrated into the soil between the soil water measurement (by neutron moisture meter) before each irrigation (generally the day before) and that after the irrigation (general two days after) allowing for drainage and ET.

$$Irrigation = \left(SWC_{after} - SWC_{before}\right) - Rain + ET + Drainage$$

where *SWC* is the soil water content from 0 - 2.1 m depth measured by neutron moisture meter generally a day before and two days after irrigation; *Rain* is the rainfall between the two measurement days; *ET* is an estimate of ET between the two measurement days using data from the ACRI weather station and a crop coefficient for the current growth stage and *Drainage* is that measured by the lysimeter over the same period.

The EC of the drainage water was measured when the collection tanks were emptied at the end of each measurement period.

During the 7 to 8 month cotton seasons, drainage varied from 74 mm in 2006/07, to 54 mm in 2008/09 to 0.7 mm in 2010/11. Under the 2009/10 wheat-fallow, there was only 23 mm of drainage in 16 months. Moreover, the amount of drainage varied considerably between irrigation events, with most drainage occurring after irrigations early in the season. Figure 3 shows there was no strong overall correlation between seasonal drainage and either total rainfall or irrigation or both during the season. However, for the three cotton seasons there was a negative correlation with seasonal rainfall (Figure 3A) and a positive one with seasonal irrigation (Figure 3B). This means there was no relationship with the total input of water from both rainfall and irrigation, suggesting that the way in which water is applied (rainfall or irrigation) is of major importance.

Table 2. Drainage and electrical conductivity of the leachate after each irrigation during the 2006/07 cotton season as measured by variable tension lysimeter, barrel lysimeter and chloride mass balance. (Amounts shown are from the date of the event until the date of the next event shown on the next row).

Event	Date	Rainfall	Irrigation infiltration*	Tension lysimeter		Barrel lysimeter		Cl mass balance
		mm	mm	Drainage, mm	EC, dS/m	Drainage, mm	EC, dS/m	Drainage, mm
Sowing	19-Oct-06	4.9		0.0				
Irrigation	24-Oct-06	40.5	107	8.8	3.1	19.0	1.5	
Irrigation	22-Nov-06	7.2	59	22.0	2.2	18.0		
Irrigation	12-Dec-06	8.3	79	34.7	2.1	38.6	2.2	
Irrigation	03-Jan-07	6.7	78	3.6	2.1	18.6	2.2	
Irrigation	16-Jan-07	13.4	75	0.2	2.2	9.3	2.2	
Irrigation	30-Jan-07	39.5	105	0.5	2.5	4.0	2.2	
Irrigation	14-Feb-07	9.3	87	2.1	2.6	4.0	2.7	
Irrigation	28-Feb-07	59.9	75	2.3	3.2	0.4	2.3	
Harvest	18-May-07							
Total for season		**189.7**	**665**	**74.2**		**111.9**		**29.1**
Rainfall + irrigation			**855**					

* Irrigation infiltration estimated as the change in profile water content (0 - 2.1 m) between neutron probe measurements made before and after irrigation allowing for rainfall, approximate ET and drainage between the two measurements.

Table 3. Drainage and electrical conductivity of the leachate after each irrigation during the 2008/09 cotton season as measured by variable tension lysimeter, barrel lysimeter and chloride mass balance. (Amounts shown are from the date of the event until the date of the next event shown on the next row).

Event	Date	Rainfall	Irrigation infiltration*	Tension lysimeter		Barrel lysimeter		Cl mass balance
		mm	mm	Drainage, mm	EC, dS/m	Drainage, mm	EC, dS/m	Drainage, mm
Sowing	09-Oct-08	200.8		5.5	3.4	16.4	1.5	
Irrigation	22-Dec-08	56.8	63	13.3	3.8	52.2	1.5	
Irrigation	12-Jan-09	0.0	102	7.3	2.9	5.3	2.2	
Irrigation	22-Jan-09	15.5	64	8.6	2.6	0.0	-	
Irrigation	05-Feb-09	89.0	103	9.3	3.6	2.4	2.2	
Irrigation	06-Mar-09	1.0	95	2.5	5.5	0.6	2.5	
Irrigation	19-Mar-09	99.6	86	7.4	8.1	0.5	2.5	
(Harvest Sowing	12-Jun-09) 23-Jun-09							
Total for season		**462.8**	**512**	**53.9**		**77.2**		**28.0**
Rainfall + irrigation			**975**					

* Irrigation infiltration estimated as the change in profile water content (0 - 2.1 m) between neutron probe measurements made before and after irrigation allowing for rainfall, ET and drainage between the two measurements.

Table 4. Drainage and electrical conductivity of the leachate after each irrigation during the 2009 wheat crop and subsequent 2009/10 fallow as measured by variable tension lysimeter. (Amounts shown are from the date of the event until the date of the next event shown on the next row). "↓" indicates there was too little drainage for collection and analysis, so drainage was accumulated over several events.

	Event	Date	Rainfall	Irrigation infiltration*	Tension lysimeter	
			mm	mm	Drainage, mm	EC, dS/m
Wheat	Sowing	23-Jun-09	0.0		0.0	↓
	Irrigation	24-Jun-09	19.1	155	0.0	↓
	Irrigation	14-Aug-09	89.9	85	1.4	13.3
Fallow	Harvest	18-Nov-09	771.4		21.6	6.6
	Sowing	4-Nov-10				
Total for season			**880.3**	**240**	**23.0**	
Rainfall + irrigation			**1120**			

* Irrigation infiltration estimated as the change in profile water content (0 - 2.1 m) between neutron probe measurements made before and after irrigation allowing for rainfall, ET and drainage between the two measurements.

Table 5. Drainage and electrical conductivity of the leachate after each irrigation during the 2010/11 cotton season as measured by variable tension lysimeter and chloride mass balance. (Amounts shown are from the date of the event until the date of the next event shown on the next row). "↓" indicates there was too little drainage for collection and analysis, so drainage was accumulated over several events.

Event	Date	Rainfall	Irrigation infiltration*	Tension lysimeter		Cl mass balance
		mm	mm	Drainage, mm	EC, dS/m	Drainage, mm
Sowing	04-Nov-10	368.3		0.4	↓	
Irrigation	20-Jan-11	0.3	87	0.1	↓	
Irrigation	02-Feb-11	41.1	49	0.1	4.9	
Irrigation	17-Feb-11	0.5	73	0.1	↓	
Irrigation	01-Mar-11	9.8	81	0.1	↓	
Irrigation	16-Mar-11	121.6	63	0.1	3.7	
(Harvest Sowing	02-Apr-11) 24-Jun-11					
Total for season		**541.5**	**353**	**0.7**		**21.0**
Rainfall + irrigation		**894**				

* Irrigation infiltration estimated as the change in profile water content (0 - 2.1 m) between neutron probe measurements made before and after irrigation allowing for rainfall, ET and drainage between the two measurements.

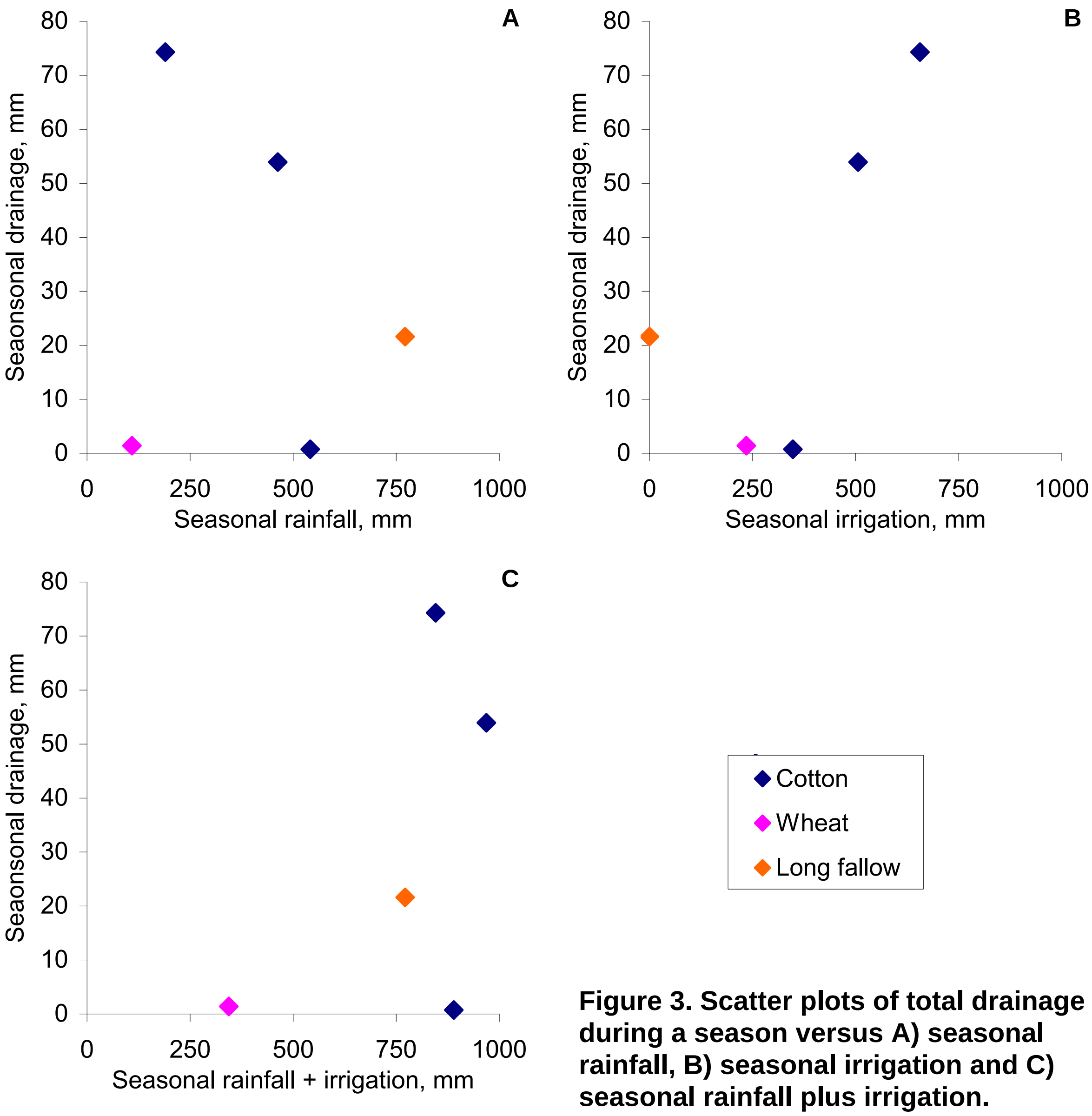


Figure 3. Scatter plots of total drainage during a season versus A) seasonal rainfall, B) seasonal irrigation and C) seasonal rainfall plus irrigation.

In 2006/07, there was very little rainfall during the season (190 mm) (Figure 4). Irrigation was necessary on the day after sowing to ensure germination and crop establishment, and was necessary throughout the season. In all there were 8 irrigations – more than in the other cotton seasons. The bulk of the drainage occurred after the second and third irrigations, and to a lesser extent after the first (Table 2). Drainage after fourth irrigation onwards was much less.

In contrast to 2006/07, in 2008/09 200 mm of early season rainfall (Figure 5) meant that the first irrigation did not occur until late December. There were a total of six irrigations. Whilst drainage was greater after the earlier irrigations than the later ones, the magnitude of drainage after the early irrigations and its contrast with that after later irrigations was not as marked as in 2006/07 (Table 3).

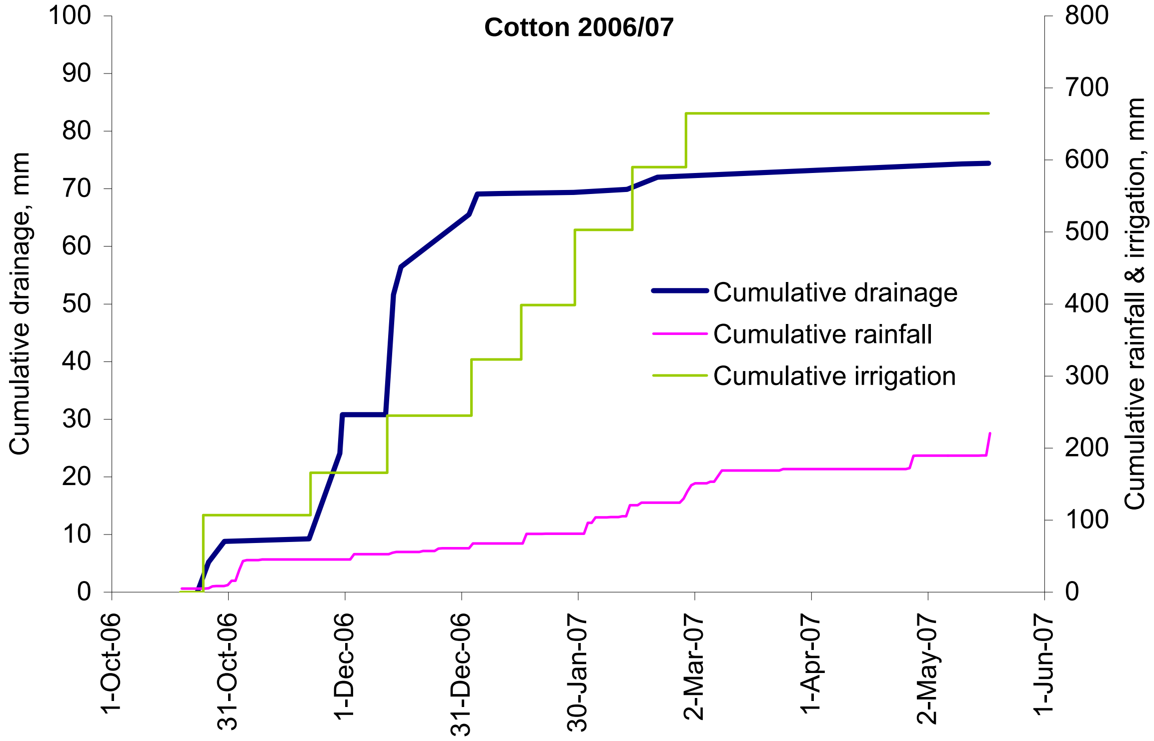


Figure 4. Cumulative drainage (left vertical axis) and cumulative rainfall and irrigation (right vertical axis) during the 2006/07 cotton season.

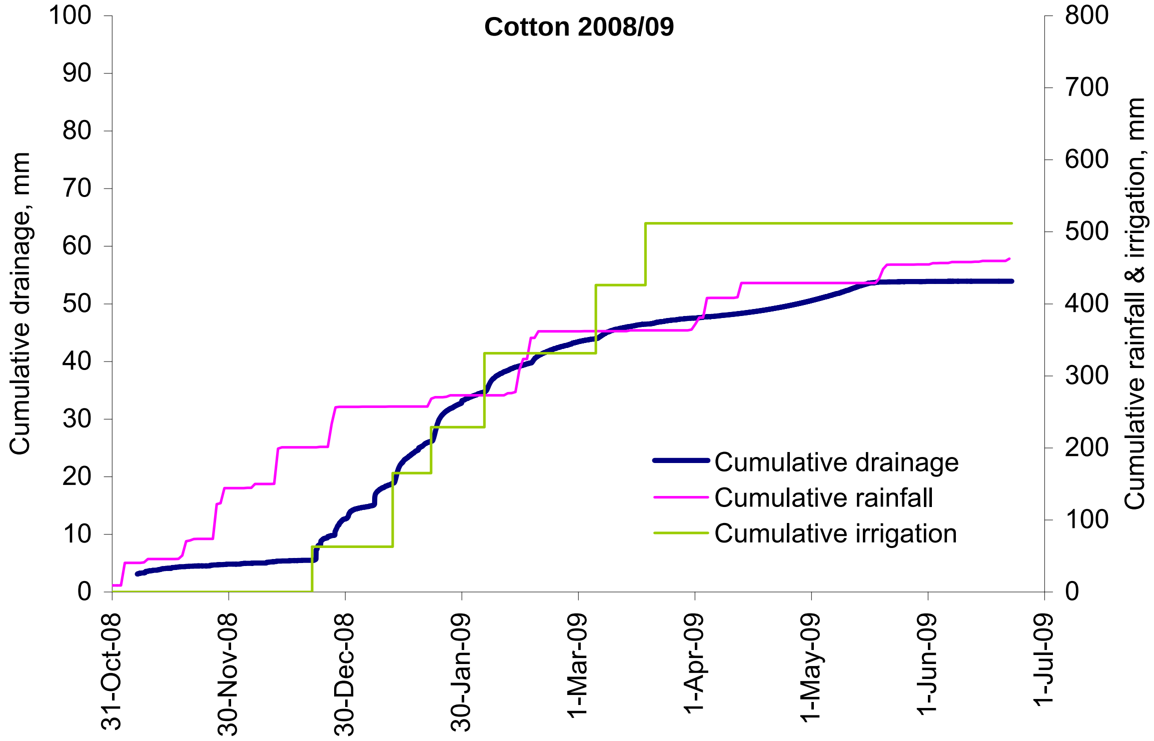


Figure 5. Cumulative drainage (left vertical axis) and cumulative rainfall and irrigation (right vertical axis) during the 2008/09 cotton season.

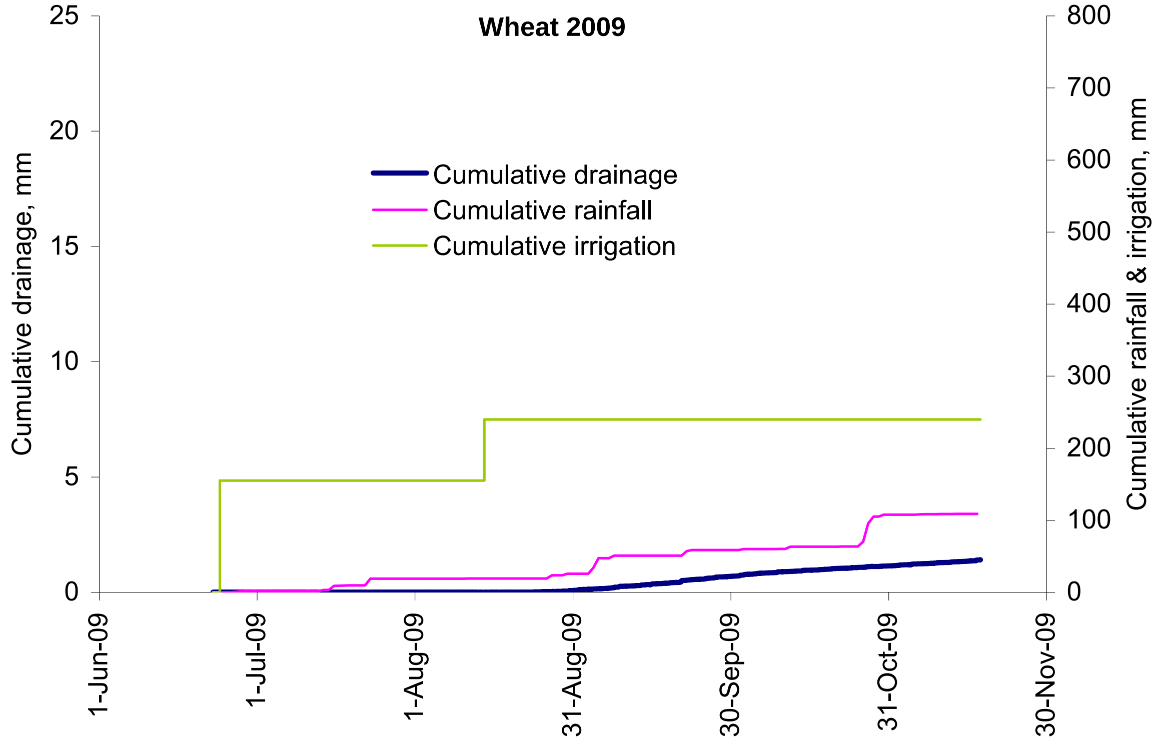


Figure 6. Cumulative drainage (left vertical axis) and cumulative rainfall and irrigation (right vertical axis) during the 2009 wheat season.

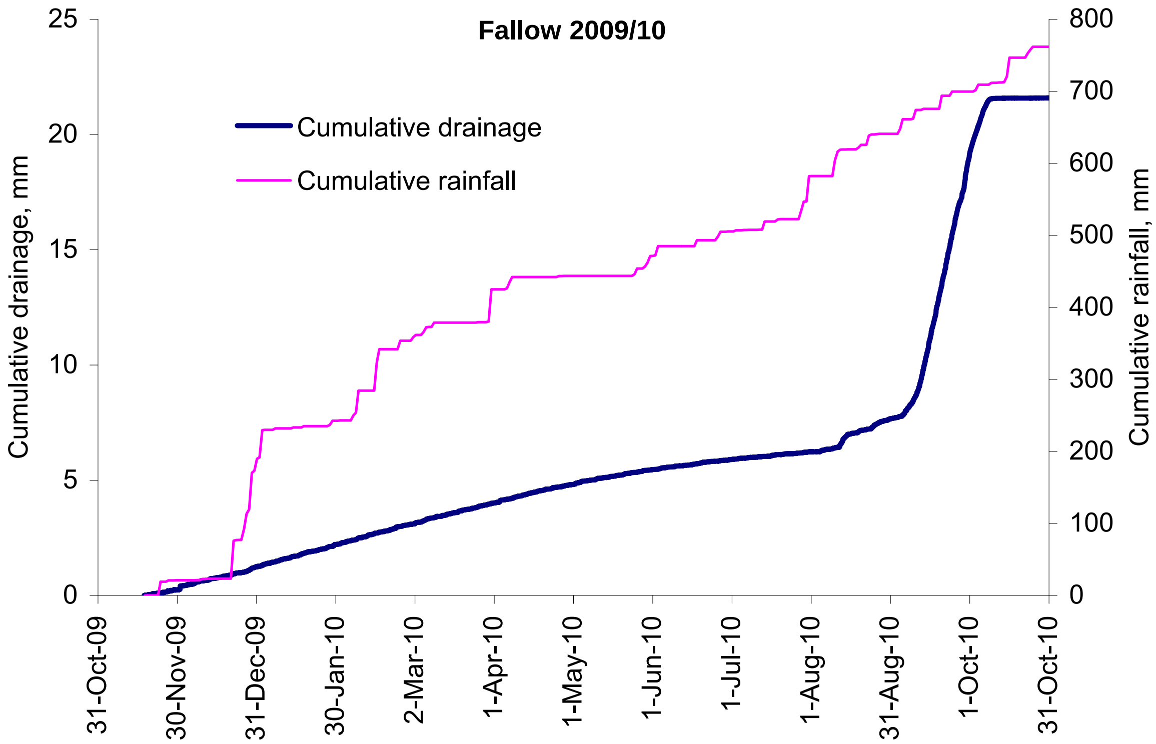


Figure 7. Cumulative drainage (left vertical axis) and cumulative rainfall (right vertical axis) during the 2009/10 fallow.

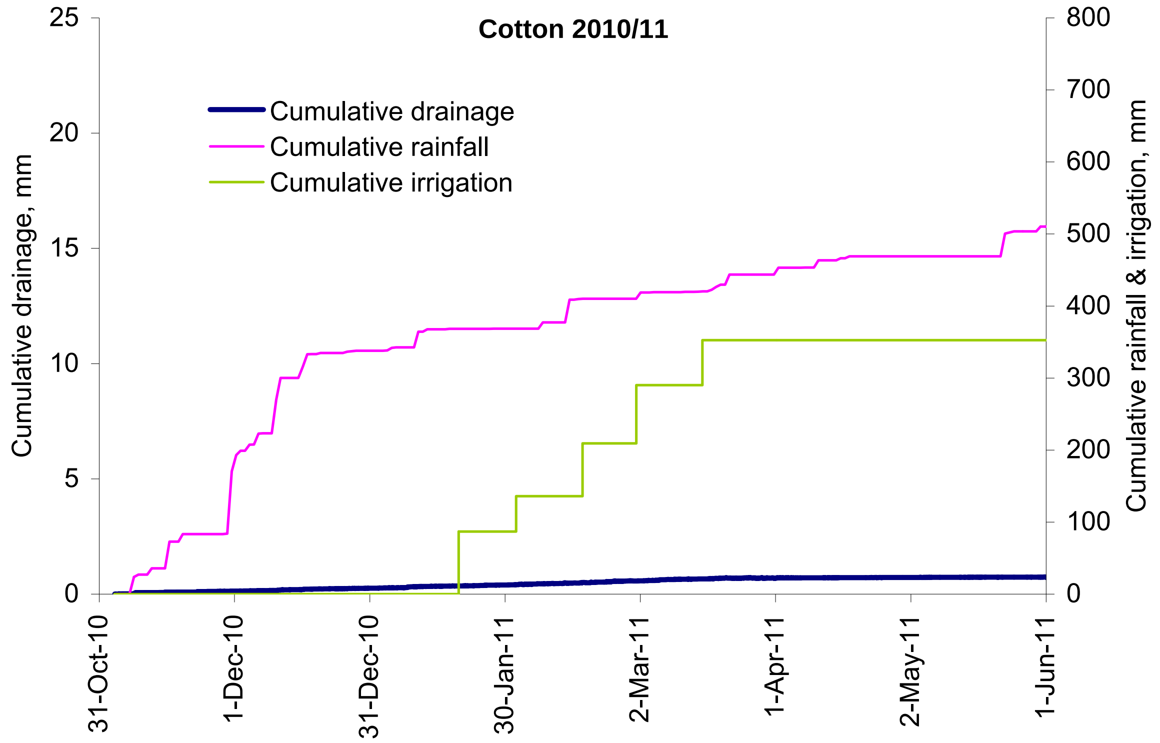


Figure 8. Cumulative drainage (left vertical axis) and cumulative rainfall and irrigation (right vertical axis) during the 2010/11 cotton season.

Like the 2008/09 cotton season, the 2010/11 season was characterised by considerable early season rainfall – 370 mm before late January when the first irrigation took place (Table 5, Figure 8). Only five irrigations were necessary and there was negligible drainage.

The 2009 wheat crop (Table 4, Figure 6) was sown in dry conditions immediately following cotton picking and received two irrigations to ensure germination and establishment. Dry conditions continued through the season and negligible drainage occurred. Over this period the drainage rate was less than 0.01 mm/day.

The subsequent long fallow from November 2009 to November 2010 received 170 mm rain during December 2009 which was followed by a steady input of 580 mm from January to October. The drainage pattern during this period (Figure 7) was unlike those during the cotton seasons which were characterised by sudden increases in the drainage rate after each irrigation. From November to August there was steady drainage at about 0.03 mm/day. However, during late August the rate started to increase, and during September it averaged 0.38 mm/day.

4.1.2 Soil water status

Soil water content

Soil water content was measured by neutron moisture meter at intervals throughout the season. The results were analysed to determine the drained upper limit (DUL) and lower limit (LL) of each of the 9 layers (Figure 9). The former was estimated as the wettest water content found two days after irrigation and the latter the driest content found during a cotton crop. Note that this LL applies only to the conditions experienced under cotton. The PAWC profile is typical of that for a Vertosol with very large PAWCs near the surface, decreasing rapidly with depth.

For simplicity the soil water content (SWC) is expressed as the soil water deficit (DUL – SWC) which shows how close each layer is to being 'full', irrespective of its absolute water content. (Wet soil with a water content equal to DUL has a deficit of zero). In addition, the 9 layers are grouped into three larger depth intervals (0.00 – 0.50 m, 0.50 – 1.05 m and 1.05 – 2.1 m). The soil water deficits over the five seasons considered in this report are shown in Figure 10A, C and E, and Figure 11A and C.

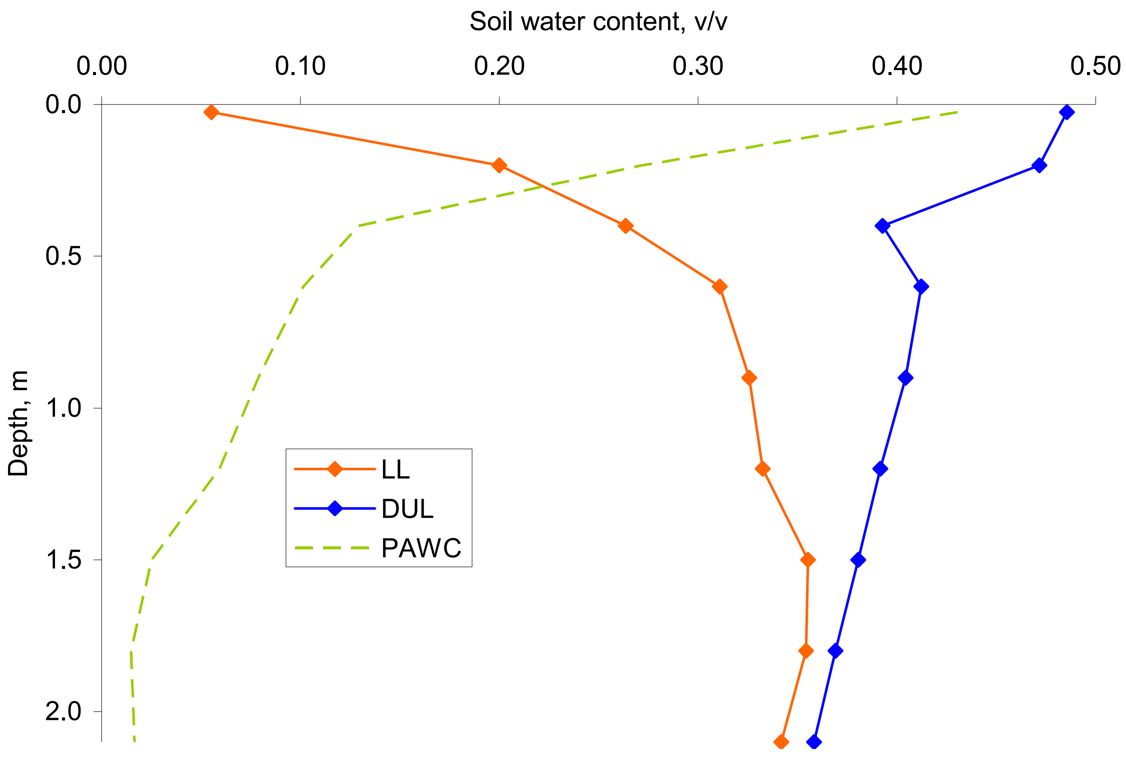


Figure 9. Drained upper limit (DUL) and lower limit for cotton (LL) for the soil profile at the ACRI lysimeter. Plant available water capacity (PAWC) is the difference between DUL and LL.

Soil water potential

The matric potential was measured continuously during the season (except the first) at 5 depths. Results are shown only for 1.8 and 2.1 m depth in Figure 10B, D and F, and Figure 11B and D. Tensiometers are notoriously troublesome as the soil dries because air enters through the ceramic cup and forms bubbles. As these become larger they increasingly distort the measurement of potential. This can only be corrected by purging the bubbles and refilling the cups at regular intervals. Unfortunately this means that when a layer is dry the data is valid for only short periods as shown in some of the figures.

Also shown in Figure 10B, D and F, and Figure 11B and D is the hydraulic gradient between 1.8 and 2.1 m. The hydraulic gradient is the driving force behind water movement, with water moving from areas of high potential (normally less negative) to areas of low potential (more negative). The gradient is calculated as:

$$Gradient = \frac{(\psi_{2.1} - gZ_{2.1}) - (\psi_{1.8} - gZ_{1.8})}{Z_{2.1} - Z_{1.8}}$$

where ψ is the matric potential (in kPa) at 1.8 or 2.1 m depth, Z is the measurement depth (in m), g is the gravitational constant (9.81 m/s^2) and the gradient is expressed as kPa/m. Positive gradients draw water upwards and negative gradients downwards. The gradient has two components – one due to the difference in matric potential and the other due to gravity. When the matric potential of two layers is equal, the gradient will be -9.81 kPa/m and water will flow only under the influence of gravity.

Drainage rate

Figure 12 and Figure 13 show details of the high frequency drainage measurement over four week periods during the 2008-09 cotton season corresponding to the intervals between irrigations. The 2006-07 season is not shown as equipment for high frequency measurement had not yet been installed. The 2010-11 season is not shown as there was negligible drainage. Figure 14 shows details of the drainage during an eight week period of high flow in August to October 2010 during the 2009/10 fallow period.

The graphs on the left of these figures show the cumulative drainage from each tray over the interval between irrigations on the left, together with the mean drainage (also shown in Figure 5 and Figure 7) and the drainage recorded by the barrel lysimeter. The graphs on the right show the drainage rate calculated over 24 hour periods.

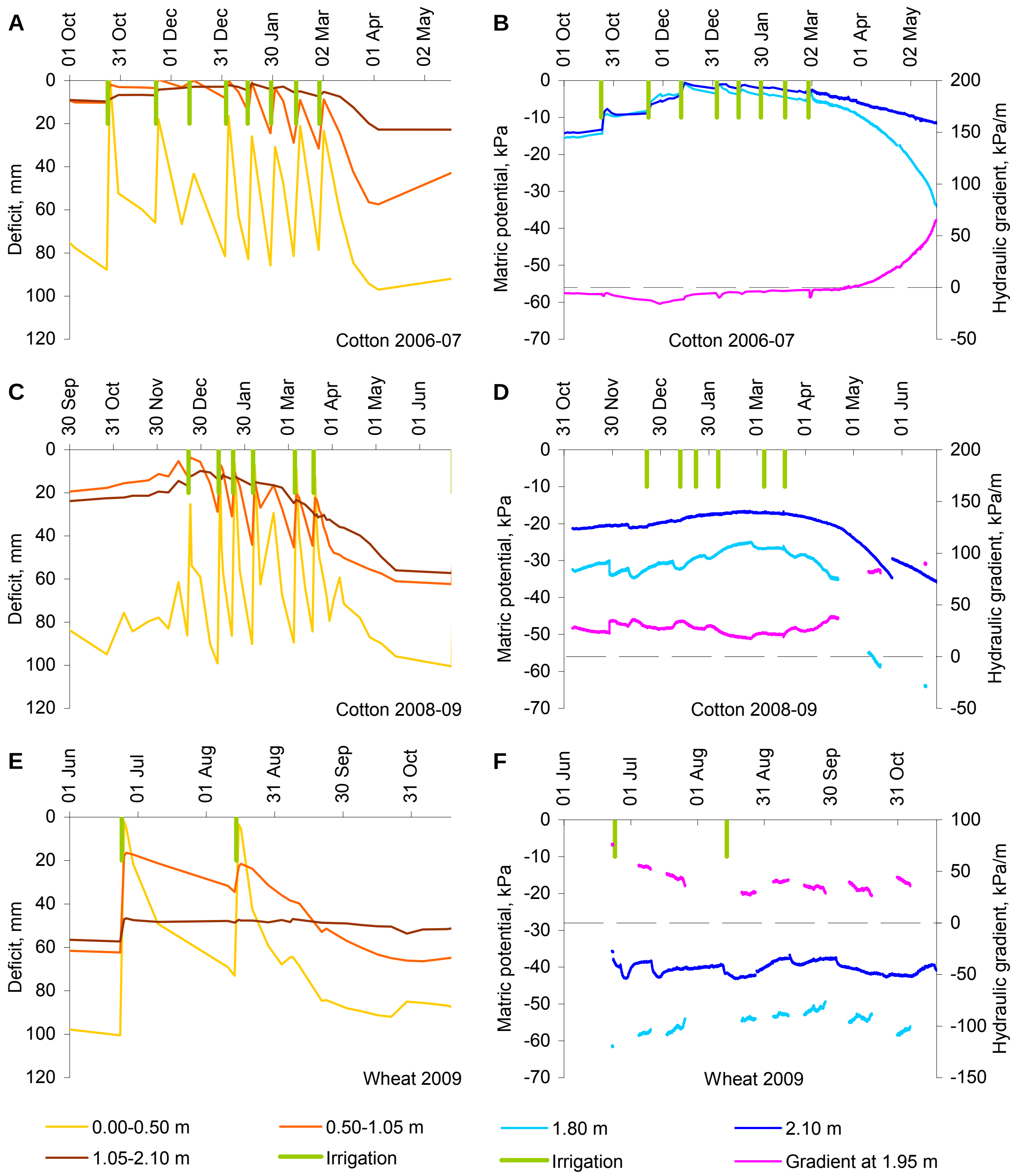


Figure 10. Soil water status during the 2006/07 cotton, 2008/09 cotton and 2009 wheat seasons. A, C and E) Soil water deficit (drained upper limit – soil water content) for three layers measured by neutron moisture meter (4 replicates). B, D and F) Matric potential (left axis) at 1.9 and 2.1 m depth measured using tensiometers (generally two replicates) and hydraulic gradient (positive upwards) between them (right axis). Gaps in the data indicate that the soil had dried out beyond the tensiometers' measurement range. Dates of irrigation events are shown as vertical bars.

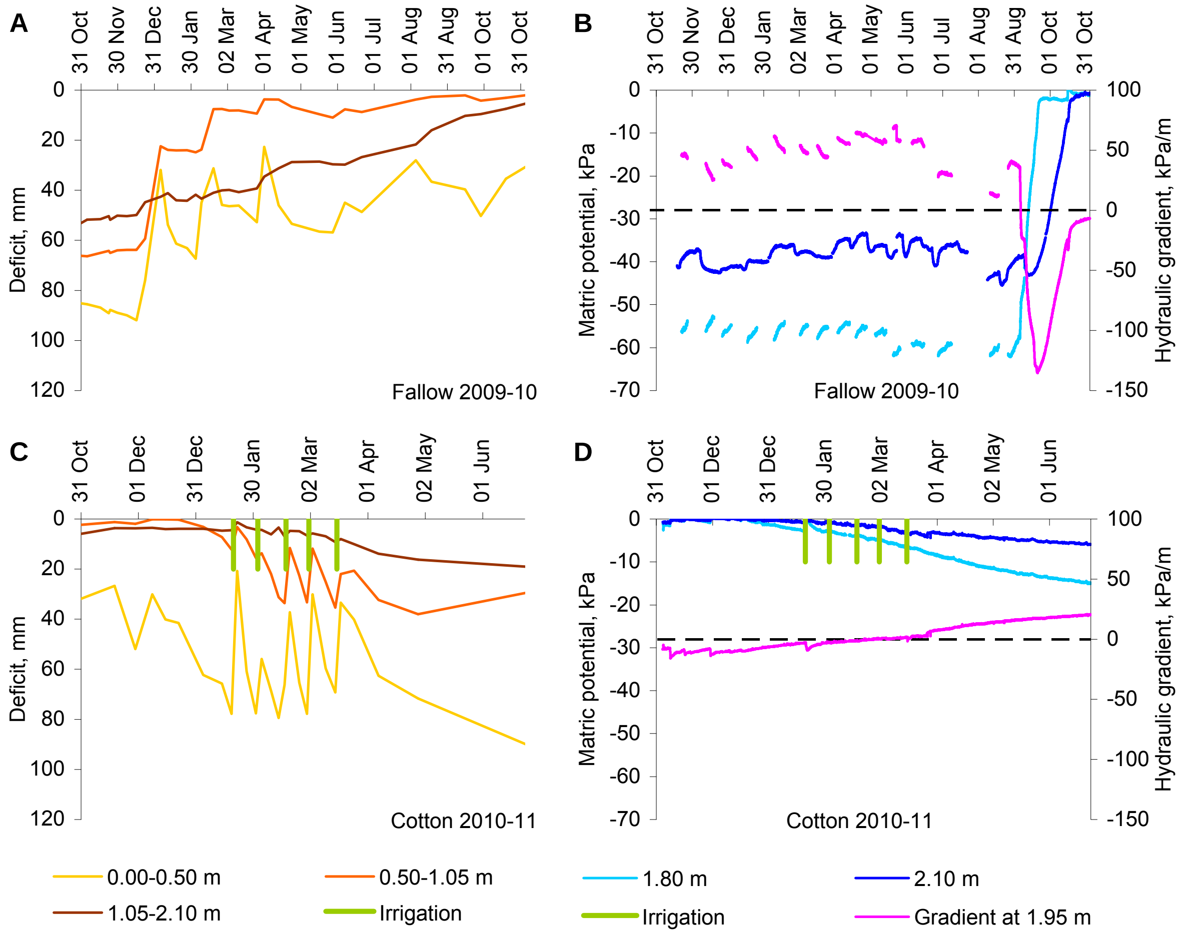


Figure 11. Soil water status during the 2009/10 fallow and 2010/11 cotton season. A and C) Soil water deficit (drained upper limit – soil water content) for three layers measured by neutron moisture meter (4 replicates). B and D) Matric potential (left axis) at 1.9 and 2.1 m depth measured using tensiometers (generally two replicates) and hydraulic gradient (positive upwards) between them (right axis). Gaps in the data indicate that the soil had dried out beyond the tensiometers' measurement range. Dates of irrigation events are shown as vertical bars.

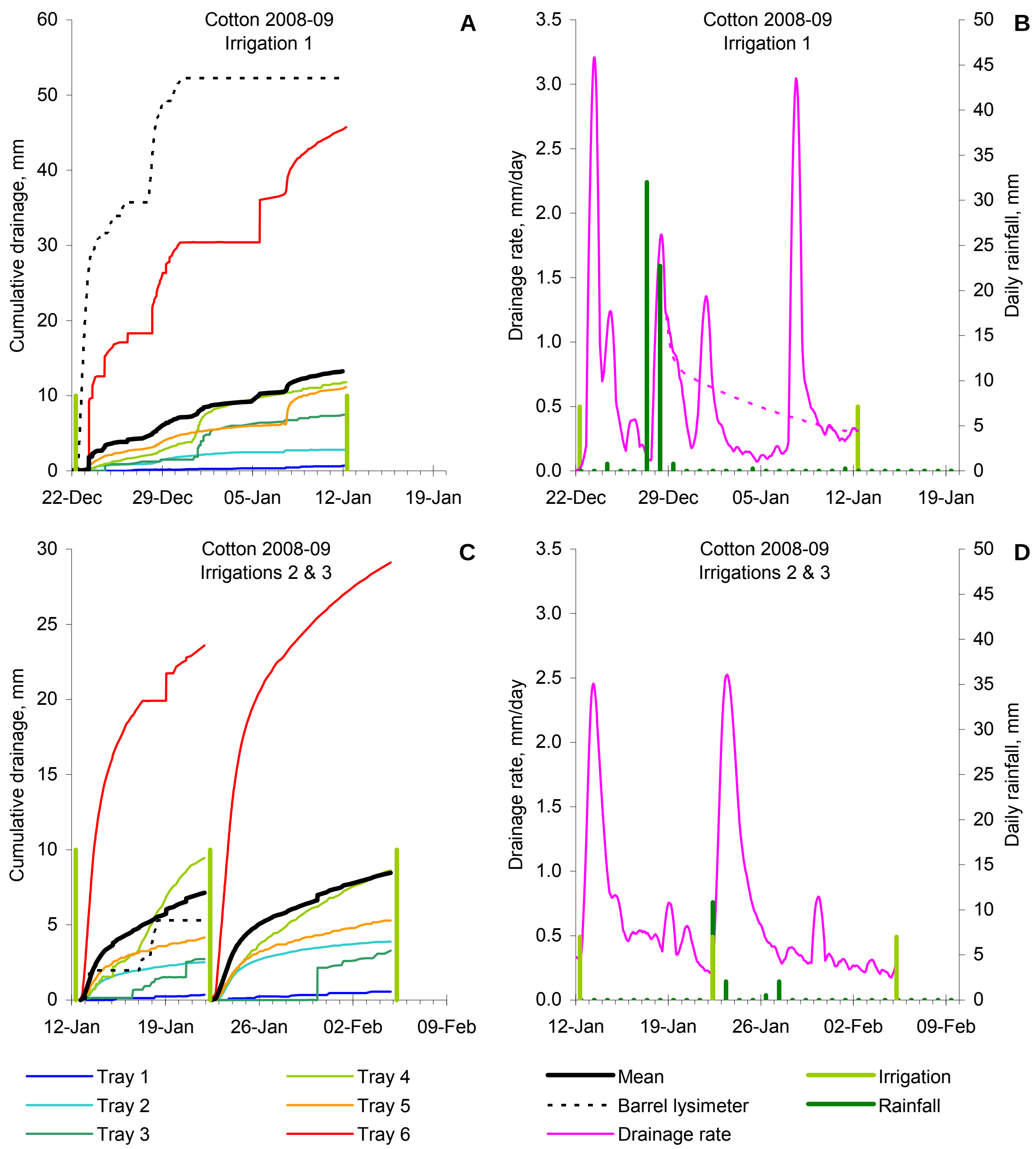


Figure 12. Details of drainage after the first irrigation (top) and second and third irrigations (bottom) of the 2008-09 cotton season. A and C) Cumulative drainage from each collection tray of the lysimeter and their mean, together with that recorded by the nearby barrel lysimeter. B and D) Mean drainage rate recorded by the lysimeter (left vertical axis) and daily rainfall (right vertical axis). Dates of irrigation events are shown as vertical bars.

Note 1: The cumulative drainage axis in C has half the range of that in A.

Note 2: The drainage rate shown after Irrigation 1 (dotted line) (B) has been corrected after 30 December to allow for air-locks in the tubing between some trays and the weighing tanks causing drainage to temporarily back-up in the trays (where it is not measured).

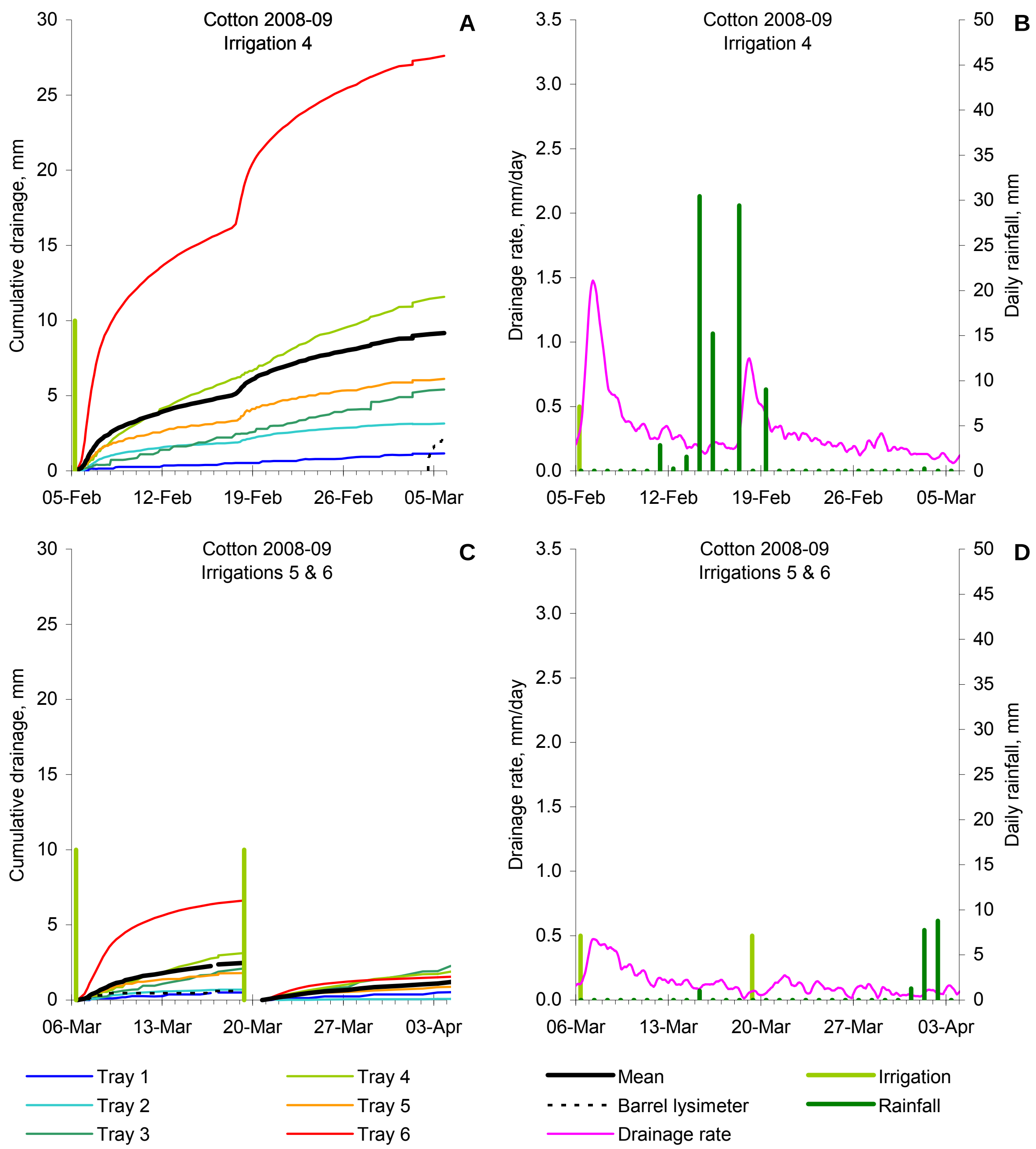


Figure 13. Details of drainage after the fourth irrigation (top) and fifth and sixth irrigations (bottom) of the 2008-09 cotton season. A and C) Cumulative drainage from each collection tray of the lysimeter and their mean, together with that recorded by the nearby barrel lysimeter. B and D) Mean drainage rate recorded by the lysimeter (left vertical axis) and daily rainfall (right vertical axis). Dates of irrigation events are shown as vertical bars.

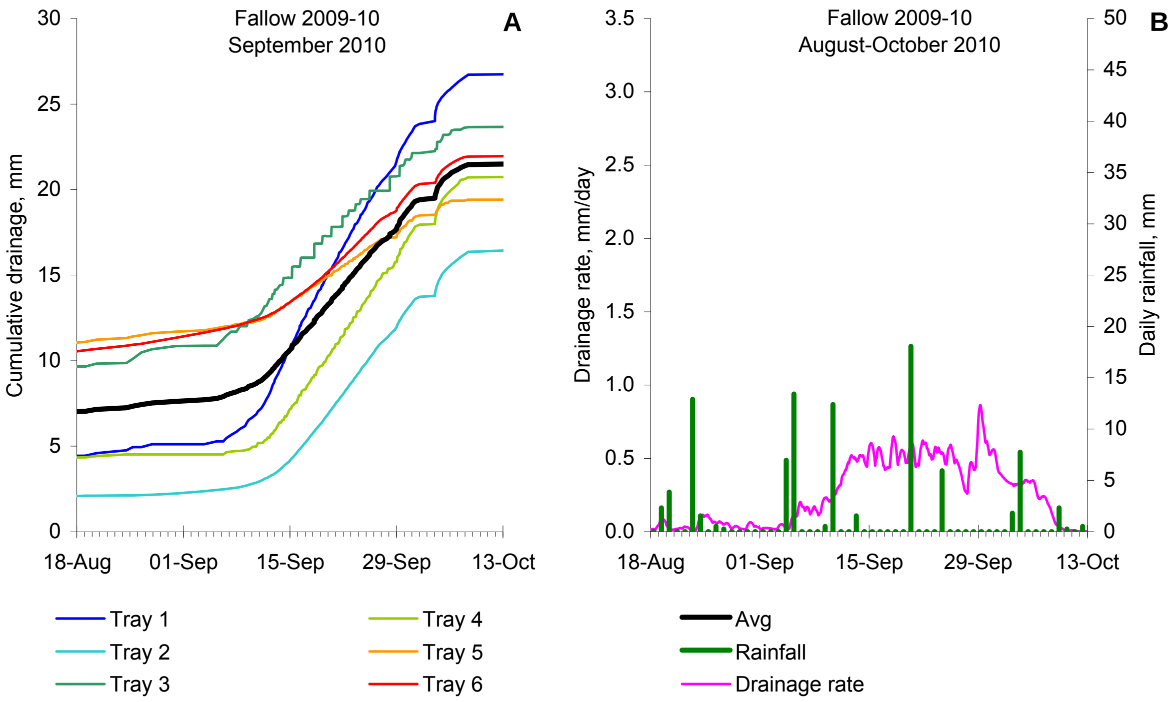


Figure 14. Details of drainage during August to October 2010 during of the 2009-10 fallow. A) Cumulative drainage from each collection tray of the lysimeter and their mean. B) Mean drainage rate recorded by the lysimeter (left vertical axis) and daily rainfall (right vertical axis).

4.1.3 Soil water behaviour

Fallow 2009/10

It is instructive to examine the behaviour of soil water by first looking at the 2009/10 fallow period as this illustrates ‘normal’ behaviour, when an input of water, in this case rain, causes a wetting front to move downward through the soil, successively wetting deeper layers until it reaches tray depth and is recorded as deep drainage.

The 2009 wheat crop dried the soil to depth (Figure 10E) by harvest, with layers nearer the surface being drier than those at depth as shown in Figure 11A. Figure 15 shows the deficits for individual layers below 0.6 m, and shows the same pattern but with greater detail in terms of depth. By December 2009 the total deficit from 0 – 2.1 m depth was 200 mm. There was a steady input of rain from December 2009 onwards, with 640 mm falling from December 2009 to August 2010 (Figure 7) which caused wetting of the soil profile starting at the surface and gradually moving down. This can be seen in Figure 15 with successive layers wetting up as the wetting front reached them. Figure 15 also shows that the wetting front became more diffuse as it travelled deeper, with the rate of water content change becoming slower for deeper layers. A very sharp wetting front reached 0.6 m at the end of December 2009, but did not reach 1.8 m until early August 2010.

Figure 11B shows the matric potential was about -55 kPa at 1.8 m and -40 kPa at 2.1 m until the end of August 2010. The hydraulic gradient was upwards at about +40 kPa/m. However, at these matric potentials the hydraulic conductivity of a clay soil is likely to be very low, so that there was little water movement despite the upward gradient. As the wetting front reached 1.8 m during August the matric potential increased very suddenly to about -1 kPa, at which potential the conductivity would have become much greater. The potential at 2.1 m was still around -40 kPa so the downward (i.e. negative) gradient between them increased from 5 September, becoming very strongly downwards and reaching a maximum of -135 kPa/m on 20 September. The strong downward gradient caused water to move downwards and wet the soil at 2.1 m. The matric potential at 2.1 m rose rapidly after 20 September until it reached about -2 kPa on 20 October. This, in turn, caused the downward gradient to decrease rapidly to about -12 kPa/m on 20 October. After this the downward gradient decreased more gradually to about -5 kPa/m.

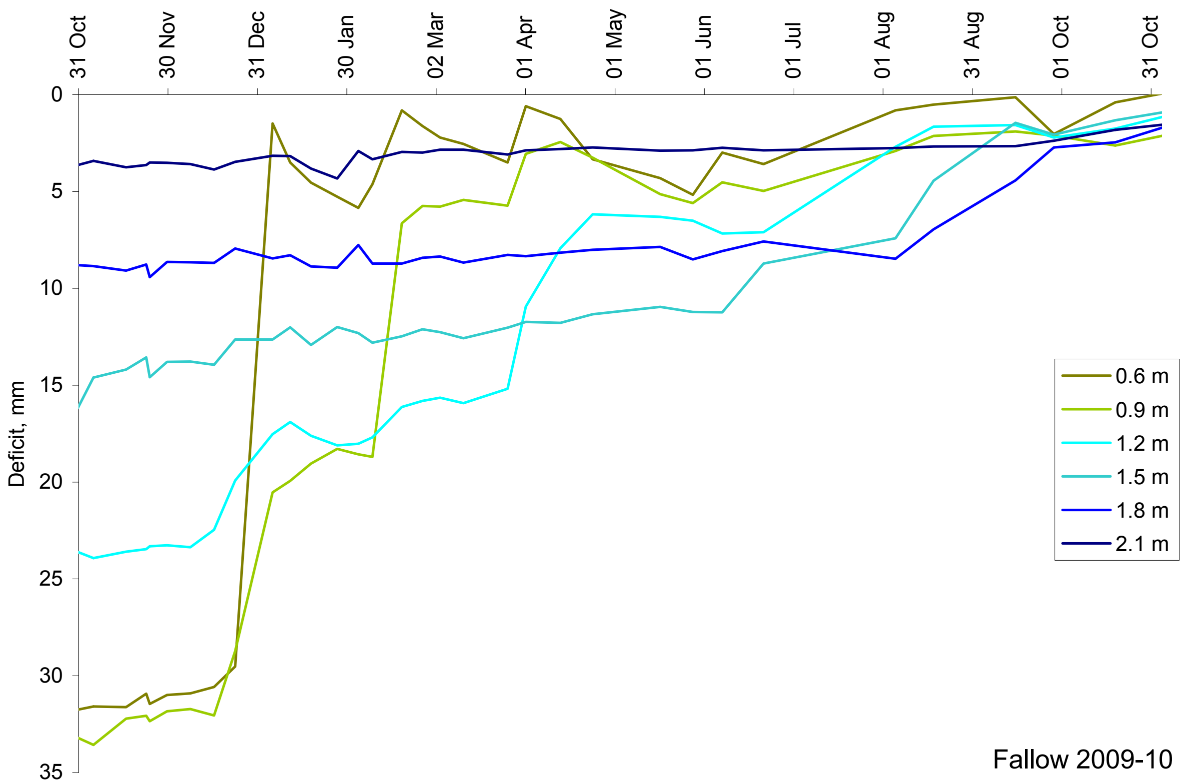


Figure 15. Soil water deficit of individual layers from 0.6 to 2.1 m depth during the 2009/10 fallow.

The drainage rate at 2.1 m started to increase on about 5 September from the very low rates measured before then (Figure 14B), and reached a maximum of about 0.5 mm/day on about 15 September corresponding to the maximum downward hydraulic gradient. The rate started to decline from about 5 October corresponding to the time when the potential at 2.1 m was rising most rapidly. By 11 October the rate had returned to very low levels.

Overall the wetting front took about a month to pass starting from the time both the matric potential at 1.8 m and the drainage rate started to increase on 5 September until the 11 October when the drainage had almost ceased.

The behaviour shown during the 2009/10 fallow helps to place that during other seasons in context and also shows that the lysimeter facility can detect and measure 'classic' wetting front behaviour.

Cotton 2006/07

The soil water behaviour during most of the other seasons did not exhibit this 'classic' behaviour. At the start of the 2006/07 cotton, the subsoil was already quite wet with deficits of only 9 mm in both the 0.50-1.05 and 1.05-2.1 m layers (Figure 10A). The matric potentials at 1.8 and 2.1 m were around -15 kPa and there was a weak downward gradient (Figure 10B). Irrigation was necessary early in the season due to a lack of rain and dry top soil conditions. The application of surface water caused immediate further wetting of the subsoil. Furthermore the young crop did not extract water from below 0.5 m over this period so that the subsoil got progressively wetter after each irrigation and was near saturation after the third irrigation. With little available storage in the subsoil these irrigations generated significant amounts of drainage (Table 2).

After the third irrigation the crop began to extract increasing amounts of water from below the 0.05-1.05 m layer generating increasingly large deficits in this layer between later irrigations. Consequently the amount of drainage after each irrigation fell with successive irrigations. From late March 2007, the deep subsoil at 1.8 m had dried sufficiently for the hydraulic gradient to be upwards.

The EC of the drainage fell over the first part of the season, but then increased towards the end of the season, reaching a maximum of 3.2 dS/m after the last irrigation.

Cotton 2008/09

The soil water deficit and matric potentials for the 2008/09 cotton season are shown in Figure 10C and D. This season provides a contrast to the previous one, because there was a more substantial deficit of 44 mm below 0.5 m at the start of the season. In addition, early season rain meant that irrigation was unnecessary until 22 December (Table 3, Figure 5). Little of this rain penetrated below 0.5 m so by the time of the first irrigation there was still a deficit of 28 mm below 0.5 m. Of the irrigation water that was not stored in the top 0.5 m, 13 mm was stored below 0.5 m and 13 mm became drainage. The situation was repeated after subsequent irrigations, but the generation of increasing deficits below 0.5 m meant there was less drainage. In summary, the presence of deficits below 0.5 m before all the irrigations, together with the lower number of irrigations (6 versus 8) resulted in 30% less drainage than in 2006/07, despite the greater input of water as rain and irrigation.

The EC of the drainage fell slightly over the first part of the season, but strongly increased towards the end of the season, reaching a maximum of 8.1 dS/m after the last irrigation.

However, there are several noteworthy behaviours. First, there was an upward gradient at tray depth all season, which should result in no drainage occurring (Figure 10D). Second, the matric potential at tray depth showed little or no response to individual irrigations despite drainage occurring. The only response was a gradual decrease in potential over the season as the subsoil dried. Both these observations suggest that water is not moving as a wetting front through the matrix of the soil profile (as described above for the 2009/10 fallow), since the tensiometers 'see' the matric potential of the soil matrix. Instead, water is moving through macropores that 'by-pass' the soil matrix, but which occupy a very small volume of the soil so that whether they are full or empty has negligible effect on the soil water content.

The implementation of high-frequency monitoring in time for the 2008/09 season provided further insight into drainage during the season (Figure 12 and Figure 13). Figure 12B and D and Figure 13B show that most of the drainage occurred in short bursts shortly after irrigations 1 to 4. The drainage rate increased very rapidly and peaked, on average, 25 hours after the irrigation front passed over the lysimeter. After the peak the rate receded slightly more slowly than it rose, but nonetheless exponentially. The peak drainage rate was 3.2 mm/day after irrigation 1 and declined to 1.5 mm/day after irrigation 4. Large rainfall events in late December 2009 and mid-February 2010 also caused similar peaks. The quickness with which the peaks occurred after irrigations and their size is further evidence that water is flowing extremely rapidly through macropores and not through the soil matrix. The peaks after irrigations 5 and 6 were much smaller (Figure 13D).

The changes in drainage EC are further evidence for by-pass flow. EC was relatively low during the first part of irrigation season but rose as the drainage rate fell after the fifth and sixth irrigations. This suggest that, during the more rapid drainage events earlier in the season, the drainage had been more diluted with irrigation water that had not equilibrated with the soil matrix.

Another interesting feature for the drainage peaks is their long tails, with drainage continuing at low but significant rates of <0.5 mm/day for weeks after the peak (Figure 12 and Figure 13). These rates were above those measured during the fallow period before the September wetting front, which were <0.01 mm/day. The drainage during these tails is still by-pass flow because during the whole season the hydraulic gradient was upwards.

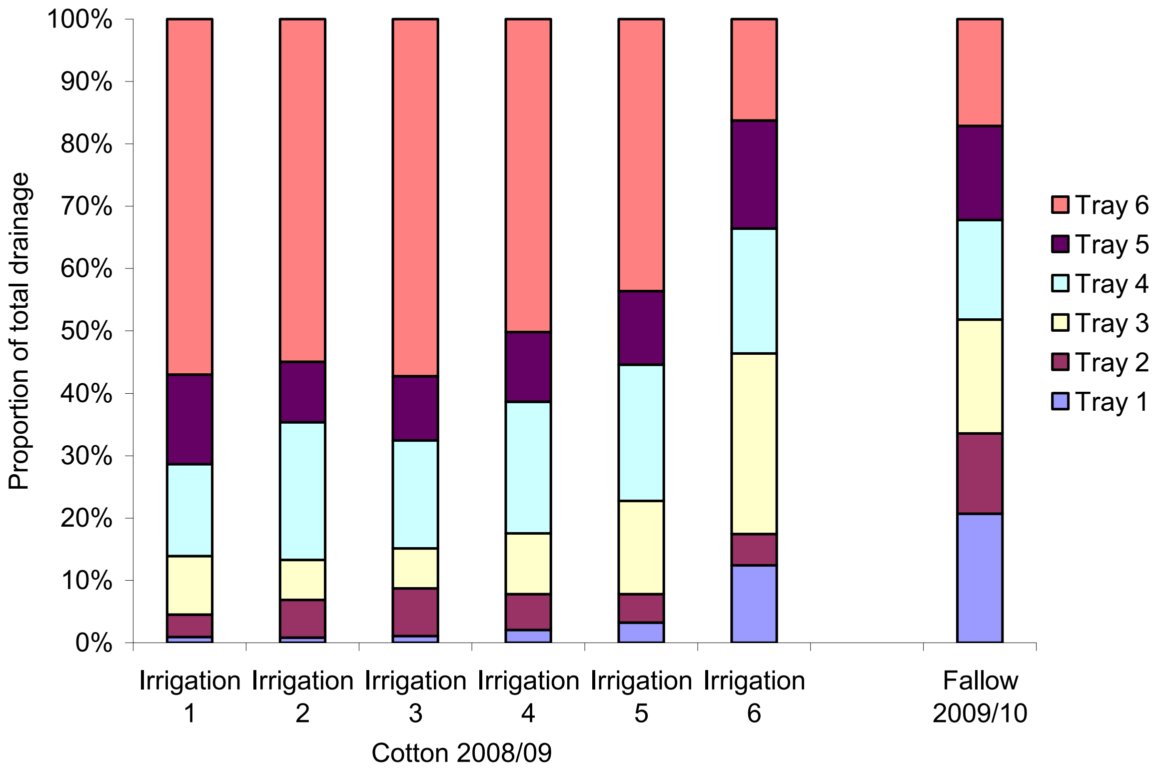


Figure 16. Proportions of total drainage collected by each lysimeter tray in the interval after each irrigation during the 2008/09 cotton season and during the 2009/10 fallow.

Drainage varied considerably between collection trays (Figure 12A and C and Figure 13A and C), demonstrating the large spatial variability of drainage over small areas – the trays cover 1.58 m^2 in total. The behaviour of each tray was consistent after the first four irrigations, with each delivering a similar proportion of the drainage (Figure 16). For example Tray 6 consistently delivered 50-55% of the total. This suggests that the large drainage rates occurring after each irrigation are due to a stable, but spatially heterogeneous, network of macropores and is further evidence for by-pass flow.

After irrigations 5 and 6, the pattern of drainage collection changed with each tray collecting more equal proportions, especially after irrigation 6 (Figure 13C). This combined with the absence of a marked peak in the drainage rate indicate that drainage after these events is dominated by flow through a more slowly conducting and more spatially homogeneous network of pores. Nevertheless, such flow can still be considered as by-pass since there is an upward gradient and the subsoil layers still have considerable empty storage.

The proportions of flow into each tray after irrigations 5 and 6 also show an interesting similarity to those during the 2009/10 fallow, during which the data indicates that flow dominated by matrix flow.

Wheat 2009

The soil water deficit and matric potentials for the 2009 wheat season are shown in Figure 10E and F. The crop was sown in dry conditions shortly after cotton picking and was irrigated the day after sowing. Unlike the 2006/07 cotton season, when the crop was also irrigated immediately after sowing generating large amounts of drainage, in this case the sub soil was very dry with a total deficit below 0.5 m of 117 mm, which absorbed 55 mm and prevented any peak in drainage. During this period the matric potential was between -50 and -60 kPa at 1.8 m and -40 kPa at 2.1 m with an upward gradient all season. Almost no drainage was recorded. This might be because the potential at 2.1 m was less than -25 kPa which is the most negative suction that can be applied to the lysimeter trays. This would prevent water moving from the soil into the trays.

Cotton 2010/11

The soil water deficit and matric potentials for the 2009 wheat season are shown in Figure 11C and D. The prolonged wet period during the 2009/10 fallow (described above) wet the soil profile by the start of the 2010/11 cotton season. As for the 2006/07 cotton season, this season started with very little subsoil deficit – only 10 mm. However, unlike the 2006/07 season, there was adequate rainfall for irrigation not to be required until late January (Table 5, Figure 8). By the time of the first irrigation the crop was already creating a deficit in the 0.5-1.05 m layer and negligible drainage was produced during the season.

The matric potentials were close to saturation for the early part of the season and showed only a moderate decrease over the season (Figure 11D). The gradient was weakly downward until mid season when it became weakly upward.

The almost total absence of drainage in the second half of the season contrasts with the earlier cotton seasons when small amounts of drainage were generated after later irrigations. The contrast is even greater because the subsoil was generally wetter than in those seasons. Observations at the site indicated that some subsoil compaction may have built up and prevented deep penetration of water, possibly disrupting by-pass flow pathways. The site was deep ripped after harvest of the cotton crop.

4.2 Predicting drainage

Apart from the drainage event during the 2009/10 fallow, the remaining drainage events do not follow the type of behaviour that can be predicted by soil physics using Richard's equation or Darcy flow approximations. However, it is widely known that by-pass flow occurs in most soils from time to time. It is understood to occur a) when there are well connected macropores that connect surface layers to deeper layers and b) when 'free' water occurs at the surface. 'Free' water refers to water at zero (or positive) potential, as when it is ponded on the surface. The latter condition is necessary because large macropores will not fill with water when the potential is even slightly negative. Thus when water is applied as rain or sprinkler irrigation, the drops are absorbed into the soil matrix and it is held at a negative potential. This water is held too tightly by the smaller pores of the matrix to be released into the macropores, until the soil reaches saturation.

When furrow irrigation is used on cracking clay soil, the two conditions for by-pass flow are met. First, furrow irrigation provides 'free' water and, second, the well developed structure of clays dominated by clay minerals (smectite) with shrink/swell properties provides a network of macropores. It should be noted that the large surface cracks characteristic of such soils, only exist in the root zone and only once the soil had dried. Below root depth there is not generally sufficient drying for the soil to crack. When there is, the weight of overlying soil (overburden) prevents crack development and instead causes the formation of failure planes or 'slickensides' between blocks of soil deep in the profile. It is possible that these slickensides act as by-pass flow paths together with other cylindrical macropores created by plant roots and soil fauna. Cylindrical macropores of up to 5 mm diameter, as well as well developed slickensides were observed at 2 m depth during excavations for installing the trays. Whilst cracks only exist when the soil is dry, cylindrical macropores and slickensides deeper in the profile are likely to be permanent and able to operate as by-pass flow paths if free water is present.

If drainage under irrigated cotton is indeed dominated by by-pass flow, it follows that predicting it will not be possible using conventional soil physics methods such as Richard's equation. However, developing a predictive model of the behaviour described above is proving difficult. Data from the lysimeter were analysed and to date it has only been possible to develop a conceptual, empirical model of drainage over the 48 hours after irrigation events, which is when the bulk of the drainage occurs.

Table 6. Properties of the model layers

	Layer 1	Layer 2	Layer 3
Depth	0.00 – 0.50 m	0.50 – 1.05 m	1.05 – 2.10 m
Lower limit for cotton (LL)	93 mm	175 mm	364 mm
Drained upper limit (DUL)	192 mm	224 mm	296 mm
PAWC	99 mm	49 mm	32 mm

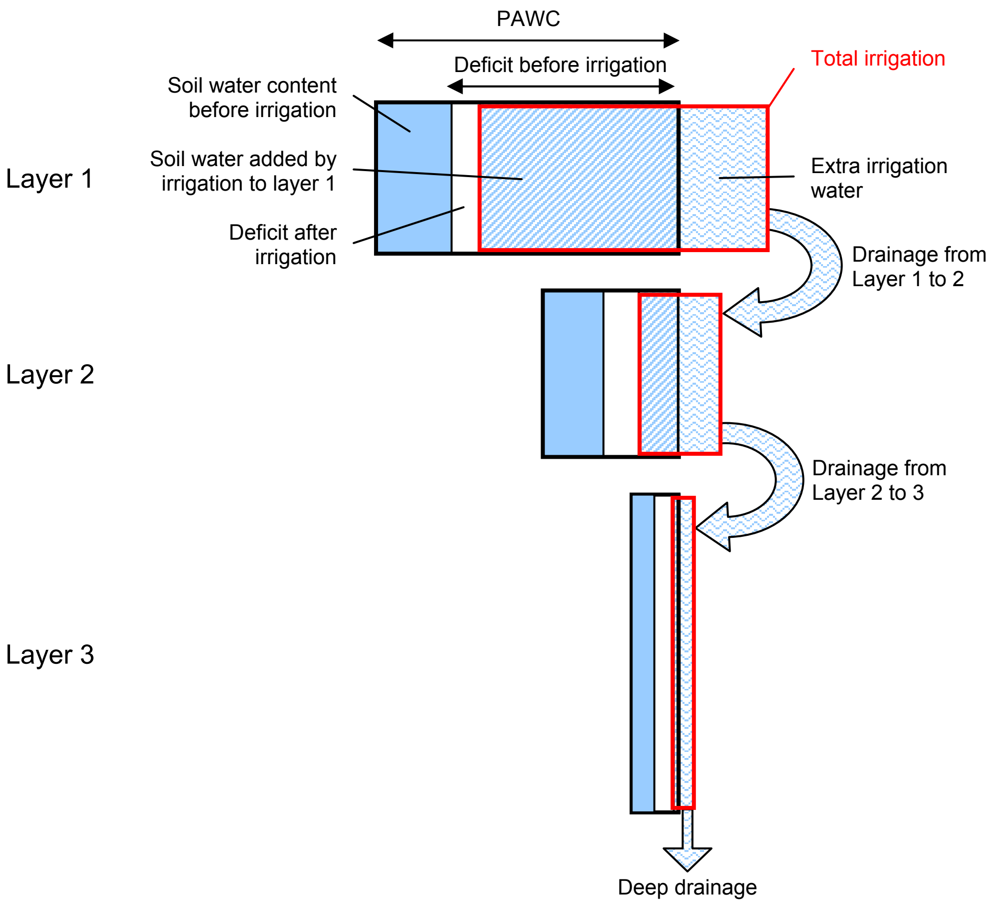


Figure 17. Conceptual model of drainage after furrow irrigation in a cracking clay soil. The area delineated by the thick black box represents the PAWC of each layer. The solid blue area is the proportion filled with water before irrigation. The remainder of the black box is the deficit before irrigation. The area delineated by the red line represents the water added to each layer. Some of this is absorbed into the soil to partly fill the deficit (diagonal hatching), leaving a portion of the deficit unfilled (white). The remainder of the of the water flows rapidly via macropores to the next layer (wavy hatching).

The model proposed for drainage during the 48 hour period after irrigation is shown in Figure 17. It adapts the simple 'tipping bucket' model that is often used in soil water balance models. In this case the soil is divided into three layers as shown in Table 6. The size of the 'bucket' is its PAWC, determined from neutron moisture meter measurements of DUL and LL as shown in Figure 9. At this stage the model only deals with a short period immediately after drainage, so it ignores the normal mechanisms for water redistribution between layers. At the start of the model for each irrigation, the water content of each layer is set to that measured immediately before irrigation. This was usually the day before, but was sometimes earlier. The water content of the topmost layer was adjusted to allow for any rain measured between the measurement and the irrigation as well as for an estimate of ET. This water content defines the pre-irrigation deficit.

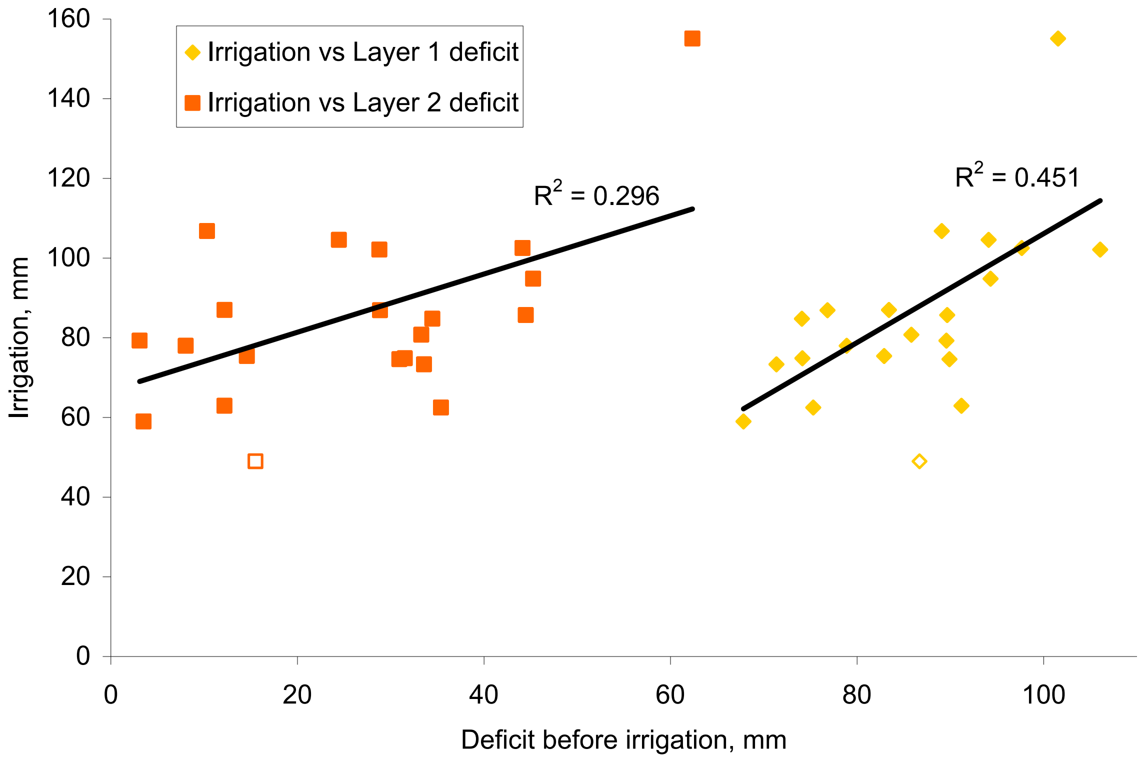


Figure 18. Relationships between the amount of irrigation infiltrated and the pre-irrigation deficits of Layers 1 and 2. Also shown are the individual regression lines for each relationship with its r^2. Hollow points have been omitted as outliers.

The first problem is to estimate how much water infiltrated during furrow irrigation. This is determined both by the properties of the soil including its pre-irrigation deficit, but is also influenced by other factors such as the gradient of the furrows and size of the siphons and the length of time they are left running. The first two factors were largely fixed for the lysimeter facility, although there were local variations in gradient over time. The time for which siphons were left running was highly variable, from zero to several hours after the irrigation front reached the tail ditch, depending on how well the beds wet up. Nevertheless, there were 'noisy', but significant relationships between the amount of irrigation that infiltrated (see Table 2 to Table 5) and the pre-irrigation deficits in Layer 1 and to a lesser extent Layer 2 as shown in Figure 18. The noise in these relationships is due to the influence of non-soil factors as well as inaccuracies in the estimation of irrigation. The multiple regression equation for the relationship that includes the deficits for both Layer 1 and Layer 2 is:

$$Irrigation = 1.119 \cdot Deficit_1 + 0.480 \cdot Deficit_2 - 22.3 \quad \text{(Eqn. 1)}$$

r^2	= 0.56
F significance	< 0.001
Probability ($coefficient_1$)	= 0.005
Probability ($coefficient_2$)	= 0.051
Probability (constant)	= 0.443

Although the amount of variation accounted for by the regression (r^2) is only 56%, the overall relationship is very significant (F significance). The regression coefficients are also significant (Probability coefficient). The significance of the regression constant (Probability constant) is generally insignificant, which is quite normal for regression analyses. Overall the relationship is highly significant, but there is unexplained variability due to factors that have not been considered, such as the length of time siphons ran for.

The next stage is to estimate the amount of water taken up by each layer. It is to be expected that the amount of irrigation water taken up by the soil would be related to the amount of empty pore space, at least near the surface. The amounts taken up by each layer (ΔSWC) in relation to their pre-irrigation deficit are shown in Figure 19.

The regression equations are as follows:

$$\Delta SWC_1 = 0.885 \cdot Deficit_1 - 10.3 \quad \text{(Eqn. 2)}$$

r^2	= 0.37
F significance	< 0.001
Probability ($coefficient_1$)	= 0.004
Probability (constant)	= 0.666

$$\Delta SWC_2 = 0.516 \cdot Deficit_2 + 2.55 \quad \text{(Eqn. 3)}$$

r^2	= 0.72
F significance	< 0.001
Probability ($coefficient_1$)	< 0.001
Probability (constant)	= 0.265

$$\Delta SWC_3 = 0.0771 \cdot Deficit_3 + 0.663 \quad \text{(Eqn. 4)}$$

r^2	= 0.22
F significance	= 0.005
Probability ($coefficient_1$)	= 0.037
Probability (constant)	= 0.360

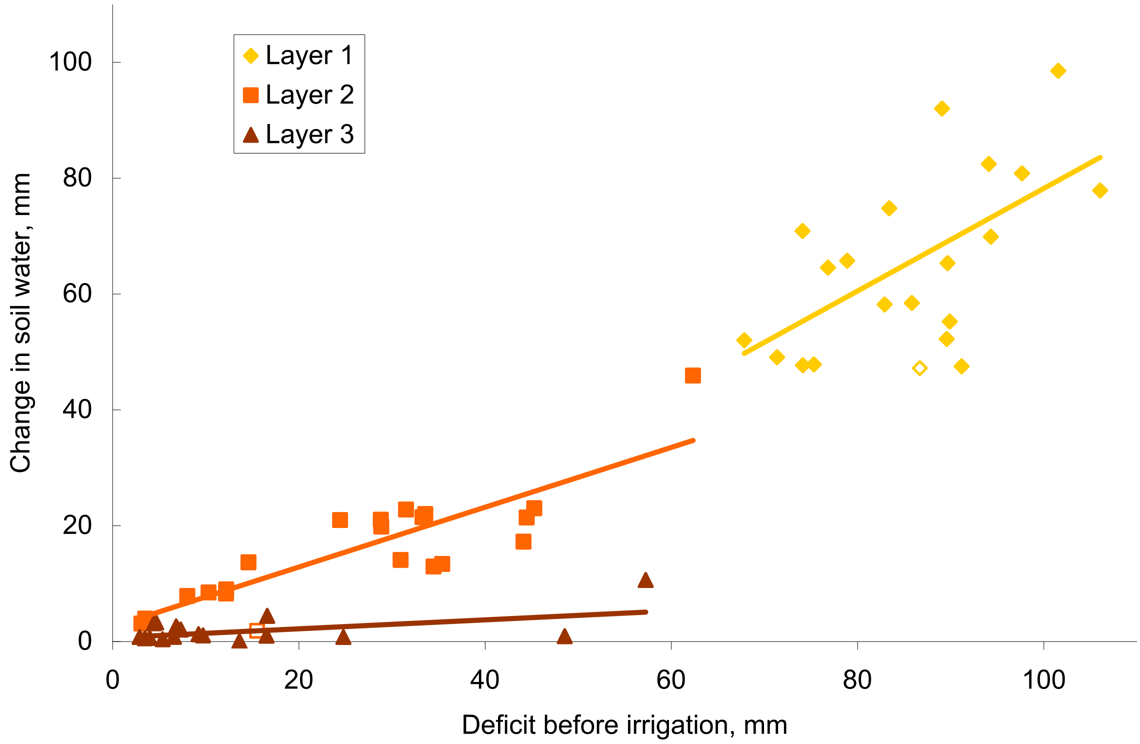


Figure 19. Relationships between the amount of water absorbed by each layer after irrigation and the pre-irrigation deficit of the layer. Also shown are regression relationships for each layer. Hollow points have been omitted as outliers.

The relationships are significant, although less so for Layer 3¸ even though the proportion of variability accounted for was low for Layers 1 and 3. The regression coefficients are also significant.

The relationship for Layer 1 indicates that the 0 – 0.5 m layer did not saturate, even though it was flooded. This was probably due to air-entrapment when dry soil was suddenly inundated with water. Equation 2 implies that after irrigation Layer 1 will still have a deficit of 17 to 22 mm for the range of pre-irrigation deficits encountered (65 – 105 mm). Equations 1 and 2 can be subtracted to give the amount of extra irrigation that was applied over and above that absorbed by Layer 1:

$$\textit{Extra irrigation} = 0.234 \cdot \textit{Deficit}_1 + 0.480 \cdot \textit{Deficit}_2 - 12.1 \qquad \text{(Eqn. 5)}$$

Conceptually this is shown in Figure 17 as 'Extra irrigation'. This water has a) infiltrated (because of the way infiltration was defined) and b) is not included in the ΔSWC for Layer 1, so can be modelled as flowing rapidly to lower layers. One result of this relationship is that the amount of extra irrigation increases as Layer 1 becomes drier (i.e. for every extra millimetre of deficit in Layer 1 0.234 mm of extra irrigation are generated. This is possibly related to the degree of cracking.

Some of the extra irrigation estimated by Equation 5 that has flowed to lower layers is absorbed into the soil. This amount is estimated by Equation 3 and decreases the amount of water that can travel to Layer 3. The absorption of the water by Layer 2 is relatively inefficient since the coefficient in Equation 3 is 0.516 mm/mm of deficit. Combining Equations 5 and 3, shows how much of the extra irrigation is available to flow to Layer 3:

$$Flow_{Layer\,2\rightarrow 3} = 0.243 \cdot Deficit_1 - 0.036 \cdot Deficit_2 - 14.6 \qquad \text{(Eqn. 6)}$$

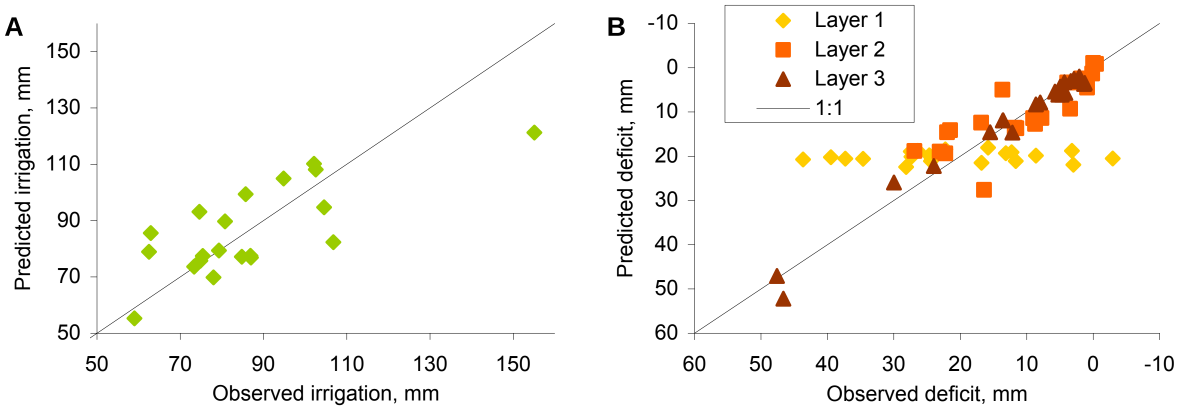
The difference between the coefficients for Layer 2 in Equations 1 and 3 (0.480 and 0.516, respectively) produces a negative combined coefficient in Equation 6 and implies that the dryness of Layer 2 could mitigate against flow to Layer 3. However, given the uncertainty in the regression models, the combined coefficient of -0.036 is unlikely to be statistically significant and therefore requires more data to confirm or discount the effect.

The absorption of the rapid flow from Layer 2 by Layer 3 is estimated using Equation 4. The deficits in this layer tend to be relatively small and the low coefficient means that very little of the flow from Layer 2 stays in Layer 3. Possible explanations for the lack of uptake by Layer 3 include a) the effect of overburden and b) that water is flowing along slickensides, whose walls are smeared due to the shearing process that created them which makes a microscopic layer with reduced conductivity.

Any water that is not absorbed by Layer 3 flows out of the profile as drainage. It is important to note that the flows described in this model are rapid flows that by-pass the matrix in the first 2 days after irrigation. The model does not deal with the slower process of water redistribution between layers.

The regression equations could be combined to estimate drainage, but this can result in negative drainage values. Instead the flow from each layer is calculated sequentially. In situations where the estimated absorption by a layer exceeds the flow to the layer, the calculated ΔSWC is limited to the amount of flow. The flow out of this layer is then modelled as zero.

The results of applying the model to the 21 irrigation events observed so far are shown in Figure 20. The model uses only the pre-irrigation soil water contents to make the predictions. As yet there are not sufficient data points to test the model on an independent set of data that has not been used to develop the model. Predictions of irrigation and the post-irrigation deficit of Layers 2 and 3 agree well with observed data. The prediction of the deficit of Layer 1 after irrigation is less good. Equation 2 predicts that, for the range of deficits encountered in Layer 1 before irrigation, the deficit after irrigation should be close to 20 mm, but there are several factors likely to influence the uptake of water by this layer that are not considered by the model, as discussed above.



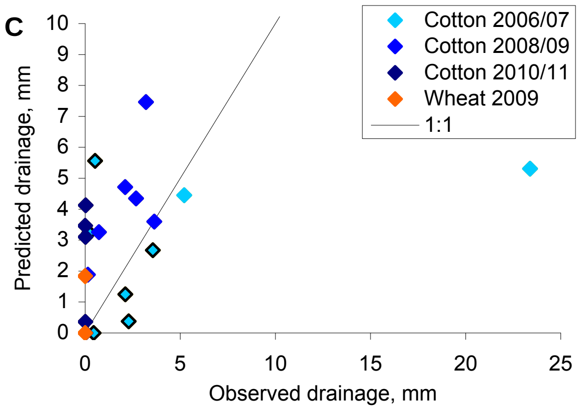


Figure 20. Model predictions of A) irrigation, B) soil water deficit after irrigation and C) drainage after 48 hours versus observed values. Outlined data during the 2006/07 cotton season are where the timing of the observed drainage measurement was not 48 hours after irrigation.

The prediction of drainage is fair. Predictions for the 2008/09 cotton season are reasonable and follow the pattern of increase and decrease through the season. The model also captures the zero drainage conditions of the 2009 wheat crop, despite it receiving the largest single irrigation of the 21 observed. Drainage was over-predicted during the 2010/11 cotton season, during which observed drainage was negligible. As discussed in Section 4.1.3, a degree of subsoil compaction was observed during this season, which may have contributed to this anomalous result. Nevertheless, the model correctly predicted that there were no high flows during the season despite the Layer 2 being relatively wet at the start of the season. The predictions for 2006/07 are mixed. Drainage amounts after irrigations 1, 2 and 4 are well predicted, but those after the other irrigations are poor. In particular, the very high drainage after the third irrigation is not captured. Predictions for the last four irrigations are either zero when drainage was observed or vice versa. One factor contributing to poor predictions, especially in the first year is inaccurate timing of measurements. After the first year soil water content measurement were generally made the day before and two days after an irrigation and drainage after 48 hours can be determined from the high frequency monitoring. In the first year, a stable measurement regime had not been determined so that for some events the pre-irrigation measurements were made several days beforehand and the post-irrigation measurements several days after. In these situations the soil water content measurements require greater adjustment for ET, which can lead to increased uncertainty. In addition, drainage measurements were made manually and do not necessarily correspond to 48 hours.

The conceptual model described above should be seen as a starting point for developing a more complete model that can be incorporated into an existing water balance model so to allow it to simulate both normal water redistribution within the soil profile as well as rapid macropore flow. This will require prediction of rapid flow over longer time periods and rapid flow generated by heavy rainfall events. One challenge is to distinguish between rapid flow and flow due to normal water redistribution.

The conceptual model and the data it is based on provide some understanding about rapid flow in cracking clay soils when they are furrow irrigated. Whilst the regression coefficients relate only to the soil at the lysimeter, the model provides a framework for investigations at other sites.

- Furrow irrigation wets the upper 0.5 m with only about 89% efficiency. This means the deficit after irrigation will still be 17 – 22 mm, probably due to air-entrapment.

- More water infiltrates during irrigation than is absorbed by the upper 0.5 m of soil. The quantity of extra water is determined by the deficits of both the 0.0 – 0.5 and 0.5 – 1.0 m layers. The extra water is 23% of the pre-irrigation deficit of the 0.0 – 0.5 m layer plus 48% of that of the 0.5 – 1.0 m layer. Thus the amount of extra irrigation increases with the dryness of the upper layer, despite the fact that the water is not absorbed by this layer. This could be due to the increasing volume of cracks as the soil dries.

- The 0.5 – 1.0 m layer absorbs some of the extra irrigation equal to 52% of its deficit. There is some evidence that as the deficit in this layer increases, it reduces the flow to lower layers. This is the reverse of the behaviour of the layer above which generates greater extra flow the drier it is. This effect is shown in Figure 21. However, this result should be treated with caution as the evidence is statistically weak. Nevertheless, it does accord with the interpretation of the results in Section 4.1.3 that the 0.5 – 1.0 m layer has a role in mitigating drainage. The result points to the need to better understand the processes involved.

- The 1.0 – 2.0 m layer appears to absorb very little of the rapid flow (only 8% of its deficit), a) because the deficits are small, b) because the amount of rapid flow is small and c) because absorption appears to be inefficient. Possible reasons include the constraint that overburden places on the absorption of water into a swelling clay at depth and the likely low conductivity of the smeared faces of slickensides which are likely to be one of the rapid flow paths. Only when the deficit is relatively large for this layer, such as after a wheat crop, does this layer have an impact on drainage

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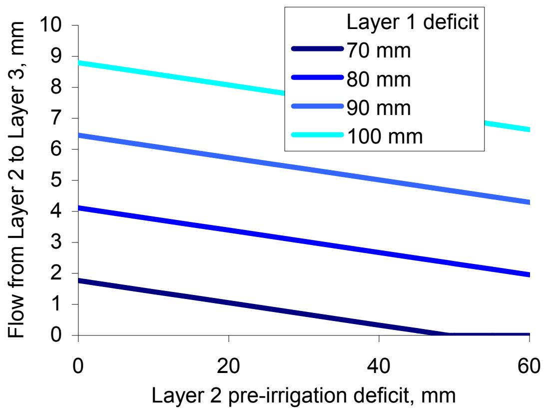

Figure 21. Nomogram (based on Equation 6) showing the effects of the deficits in Layers 1 (0.00 – 0.50 m) and 2 (0.50 – 1.05 m) on the amount of rapid flow below 1.05 m. Whilst increasing the deficit in Layer 1 increases the flow, the reverse applies to Layer 2.

4.3 Other methods of estimating drainage

One objective for the ACRI lysimeter was to benchmark the performance of other less expensive methods of estimating deep drainage. Two alternative methods were compared to the lysimeter – barrel lysimeter and chloride mass balance.

4.3.1 Barrel lysimeter

The drainage collected by the barrel lysimeter nearest to the tension lysimeter was compared to that from the tension lysimeter for the 2006/07 and 2008/09 cotton seasons, after which the barrel lysimeters became inoperable because of deterioration in the seals holding vacuum in the system. Results are shown in Table 2 for the 2006/07 season and in Table 3 for the 2008/09 season. The barrel lysimeter recorded 51% more drainage than the tension lysimeter during the first season and 43% more in the second. During the first season the barrel lysimeter greatly overestimated drainage after the first, fourth and fifth irrigations. It provided more reasonable estimates after the other irrigations. During the second season it greatly overestimated between sowing and the first irrigation and after the first irrigation. It underestimated drainage after the remaining irrigations. Thus the 40-50% overestimation for the seasonal totals masks much greater inaccuracies, both over and under, for individual events.

The barrel lysimeter seems to overestimate early in the season when the drainage is greatest and underestimate later in the season when drainage is smaller. During 2008/09, high frequency measurements were made by both instruments, which allows detailed comparison of their performance (Figure 12A, C and Figure 13A, C). After the first irrigation (Figure 12A), the barrel lysimeter responded almost instantly after the irrigation front passed overhead, whereas the tension lysimeter responded after a few hours. The response exceeded that of all six trays. The same level of response occurred after heavy rain on 27-28 December 2008. After the second irrigation (Figure 12C) the response was within the range of the six trays. However, there was no response by the barrel lysimeter after the remaining irrigations, except a small, very delayed one after the fourth irrigation (Figure 13A).

Another discrepancy between the two methods is that the EC collected by the barrel lysimeter is almost always less than that collected by the tension lysimeter (Table 2 and Table 3). This indicates the drainage collected by the barrel lysimeter has a greater proportion of by-pass flow, because its EC has been more diluted by irrigation water.

Reasons for the discrepancies between the barrel lysimeter and the tension lysimeter are likely to be a mixture of the following:

Field variability: Results from the different trays of the tension lysimeter indicate that drainage after furrow irrigation is very variable over even short distances. The only way to overcome this is to use more instruments or to increase their size. However, the barrel lysimeter measures drainage over a much smaller area (0.07 m^2) than even one of the tension lysimeter trays (0.26 m^2) – a 3.7× difference. It is possible that the site of the barrel lysimeter was unlucky and that it was placed in an area with drainage rates at the upper end of the spatial variability. However, the rates recorded after irrigation 1 of 2008/09 are outside the range of any of the six tension lysimeter trays. The area of the barrel lysimeter is likely to be too small to adequately represent the scale of soil structure in this cracking soil and the distance between irrigated furrows (2 m).

Soil disturbance during barrel lysimeter installation: Barrel lysimeter installation in May 2005 involved drilling a large core from the surface. After installation the hole was backfilled, largely with several lengths of intact soil core. However, the annulus created by the proline drill had to be filled with disturbed soil. Cultivation for the 2005 wheat crop could be expected to have restructured the surface soil, along with wetting-drying cycles due to rainfall. Restructuring of the deeper subsoil likely occurs only when the profile is wet and dried to depth by irrigation. At the start of the 2006/07 cotton season the barrel lysimeter had been in place for 17 months. The overestimation by the barrel lysimeter during 2006/07 may be because it was still in its 'settling in' period. However, the pattern of overestimation of large drainage events continued two years layer during the 2008/09 season. The very rapid response after the first irrigation of 2008/09 could point to highly conductive pathways due to soil disturbance being more permanent than first thought. The lower EC of drainage collected by the barrel lysimeter suggests the same.

Difference in operation mode: The barrel lysimeter applied a constant, small potential at 2 m depth. The total potential was about -22 kPa (equivalent to -2.25 m H_2O), of which -20.6 kPa is required to lift the drainage 2.1 m to the measurement device. The remaining -1.5 kPa ensures that drainage is collected even when the soil is not saturated. On the other hand, the variable tension lysimeter, tracks the changes in suction at tray depth to maintain 'hydraulic invisibility'. The constant tension applied to the barrel lysimeter is a compromise that may lead to overestimation when the soil is saturated (*i.e.* it is 'sucking' more than the soil), but underestimation when the soil is drier and the potential of the soil is more negative than -1.5 kPa. The barrel lysimeter has 0.35 m high walls designed to allow drainage to build up in the soil contained within the 'barrel' until it reaches a potential greater than -1.5 kPa at which point it can be collected. However, if the surrounding soil starts drying again before the soil in the barrel reaches this potential, the built up water will simply be sucked out of the barrel into the surrounding soil and nothing will be measured. For the majority of the time the barrel lysimeter is probably in the latter state with the soil too dry for the device to collect drainage. However, underestimation during these periods is eclipsed by the magnitude of the overestimation when the soil is wetter. A further complication is that the potential applied to the barrel lysimeter is not, in fact, constant. The application of -1.5 kPa to the barrel lysimeter relies on the vacuum/drainage tube from the lysimeter to the collection device being full of water all the time. However, it was observed that air-entry into the ceramic candles in the barrel lysimeter frequently caused bubbles to form in the tube or caused it to empty all together, resulting in suctions anywhere between -1.5 and -22 kPa being applied to the candles.

4.3.2 Chloride mass balance

Table 2, Table 3 and Table 5 show the estimates of seasonal drainage made for the 2006/07, 2008/09 and 2010/11 cotton seasons. In the first two seasons chloride mass balance underestimated drainage by 61% and 48%, respectively. However, in 2010/11, it estimated 21 mm compared to 0.7 mm by the tension lysimeter. The latter result was probably because the subsoil compaction described earlier was localized to the vicinity of the lysimeter, where it reduced drainage to negligible values, whilst the soil cores for chloride mass balance were sampled from all over the plot.

The chloride mass balance method assumes that water moves as a uniform front through the soil, moving chloride with it. However, to the extent that there is 'by-pass' flow through macropores, some water applied to the surface will 'by-pass' the soil matrix and not mix with soil solution in the matrix. This leads to underestimation of drainage. As discussed above there is evidence that much of the drainage is generated as rapid, by-pass flow.

4.4 Water quality of drainage

4.4.1 Salts

Table 2 to Table 5 show the EC (calculated as a volume-weighted mean) of the drainage over each season. The volume-weighted mean EC over the whole period was 3.7 dS/m, and most of the time the EC was between 2 and 4 dS/m. For comparison the mean EC of the irrigation water was 0.39 dS/m. The higher EC of the drainage is due to a) ET causing accumulation of salts contained in the irrigation water, and b) the mobilisation of salts stored naturally in the profile over long periods due to processes such as weathering and accumulation of salt in rainfall. Over the whole measurement period, the profile received 1769 mm of irrigation and 2074 mm of rainfall. Of this total input of 3843 mm, 152 mm or 4% became drainage, with 96% becoming ET (assuming none of the rainfall is lost as runoff). These totals suggest that the EC of the drainage should be about 4.5 dS/m (i.e. $0.39 \times 1769 / 152$), assuming rainfall has negligible EC. The discrepancy indicates that there was an overall accumulation of salt in the profile over the measurement period, although it is not known what happened in the 17 months between the 2006/07 and 2008/09 cotton seasons when the lysimeter was not operating.

The mean pH of the drainage was about 9.6, compared to that of the irrigation water which was 8.3. From the 2008/09 cotton season onwards the inorganic chemistry of the drainage was analysed. The ranges in concentration of various ions are shown in Table 7.

The relative amounts of Na, K, Ca, Mg and EC are plotted over time in Figure 22 together with EC. Na and K are both correlated with EC and follow the same pattern during the entire period. Ca follows the same pattern over time as Cl. Mg follows Ca and Cl during the 2008/09 cotton season, but follows Na, K and EC over the subsequent period.

Table 7. Mean concentrations of various ions in and the mean EC of drainage collected at the ACRI lysimeter and in the irrigation water.

	EC dS/m	Cl mg/L	Na mg/L	K mg/L	Ca mg/L	Mg mg/L
Mean in drainage	5.55	113	1390	15.1	6.20	50.3
Std dev in drainage	2.99	192	631	6.19	3.08	47.4
Mean in irrigation water	0.39	25	68	5.2	31.4	15.9

It appears that drainage early in the 2008/09 season had high concentrations of Na and K and high ECs. All these parameters decreased during the part of the irrigation season when drainage was greatest. As drainage decreased later in the season, so Na and K and EC started to increase again. During the subsequent period of very low drainage during the 2009 wheat crop they rose to their highest values during the measurement period. The values following the arrival of the wetting front at tray depth in September 2010 were still high relative to those during the 2008/09 cotton season. It is difficult to resolve the pattern for the 2010/11 cotton season because so little drainage was generated that it could only be collected on two occasions. This meant the drainage from different stages of the irrigation season were likely to be mixed together – the low values of EC, Na and K late in the season seem to follow the pattern for the middle of the irrigation season.

The time series for EC, Na and K suggests that drainage with a chemical 'signature' with relatively high EC, characterised by high Na and K was derived from the soil matrix since it occurred during periods of low drainage. The high values at the start of the 2008/09 cotton season and during the wheat and fallow periods probably represent water flushing salts from the matrix that had accumulated during the irrigation season. Given the relatively low concentration of Cl during these periods, the cations must have been balanced by other anions, most likely bicarbonate or hydroxyl ions since the pH was greater than 8.3.

The pattern for Cl and Ca was for their concentrations to be greatest when drainage was greatest – that is after the early irrigations of the 2008/09 cotton season and when the wetting front passed tray depth in September 2010. Thus the chemical signature of drainage with relatively high concentrations of Cl and Ca and relatively low concentrations of Na and K ions probably represent rapid by-pass flow, closer in composition to the irrigation water, in which cations are balanced by Cl rather than bicarbonate of hydroxyl ions. The high values in drainage collected late in the 2010/11 cotton season follow the pattern for by-pass flow (as do the values for EC, Na and K). This suggests this drainage was generated during the middle of the irrigation period, although it was only collected later due to the small volume of drainage.

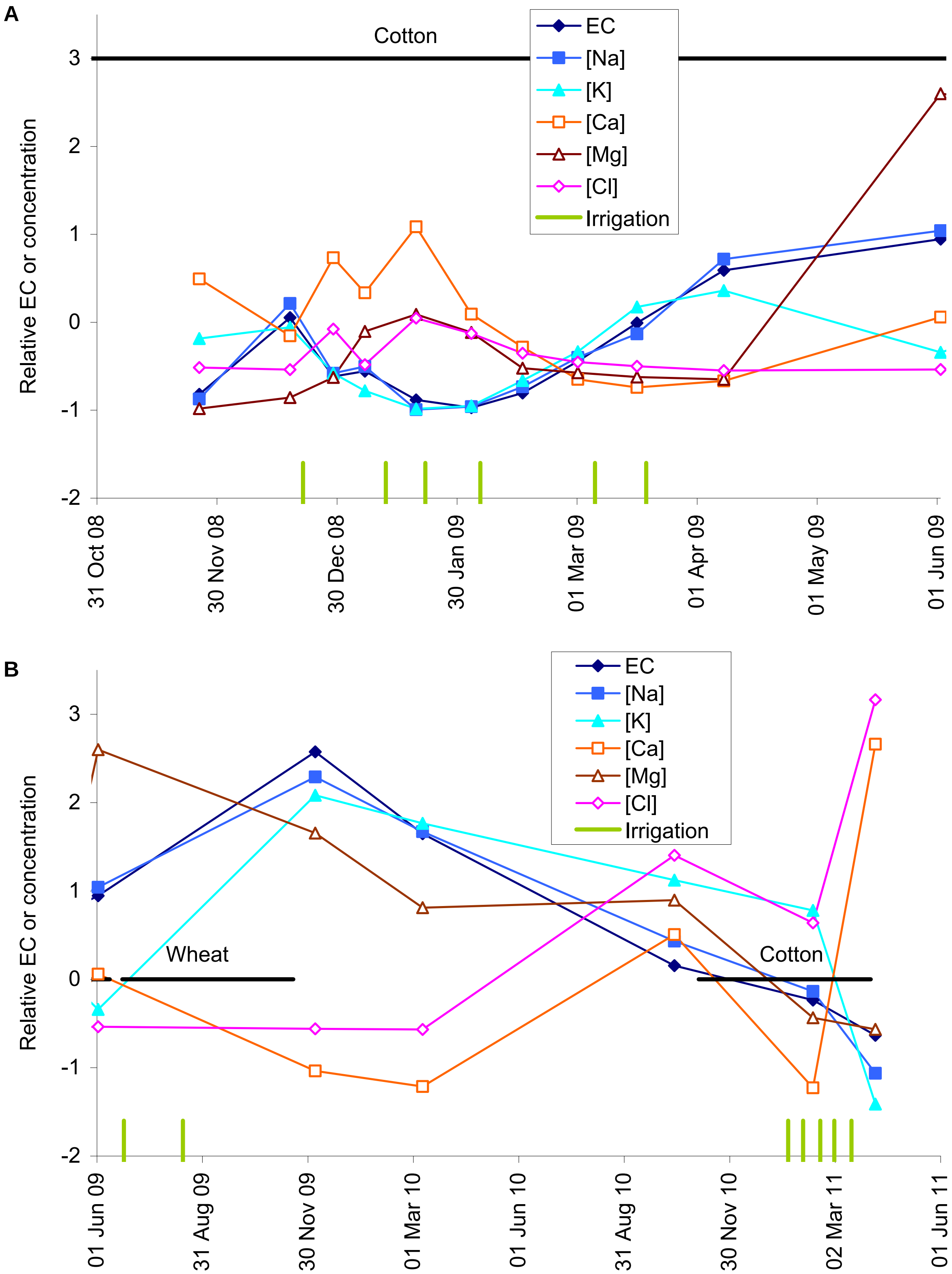

Figure 22. Relative concentrations of various cations and Cl, and EC in drainage water A) during the 2008/09 cotton season and B) during the 2009 wheat, 2009/10 fallow and 2010/11 cotton seasons. The concentrations for each ion or EC are expressed relative to the range of values encountered for the same ion or for EC (i.e. not relative to each other). The relative values are standard deviates from the mean value.

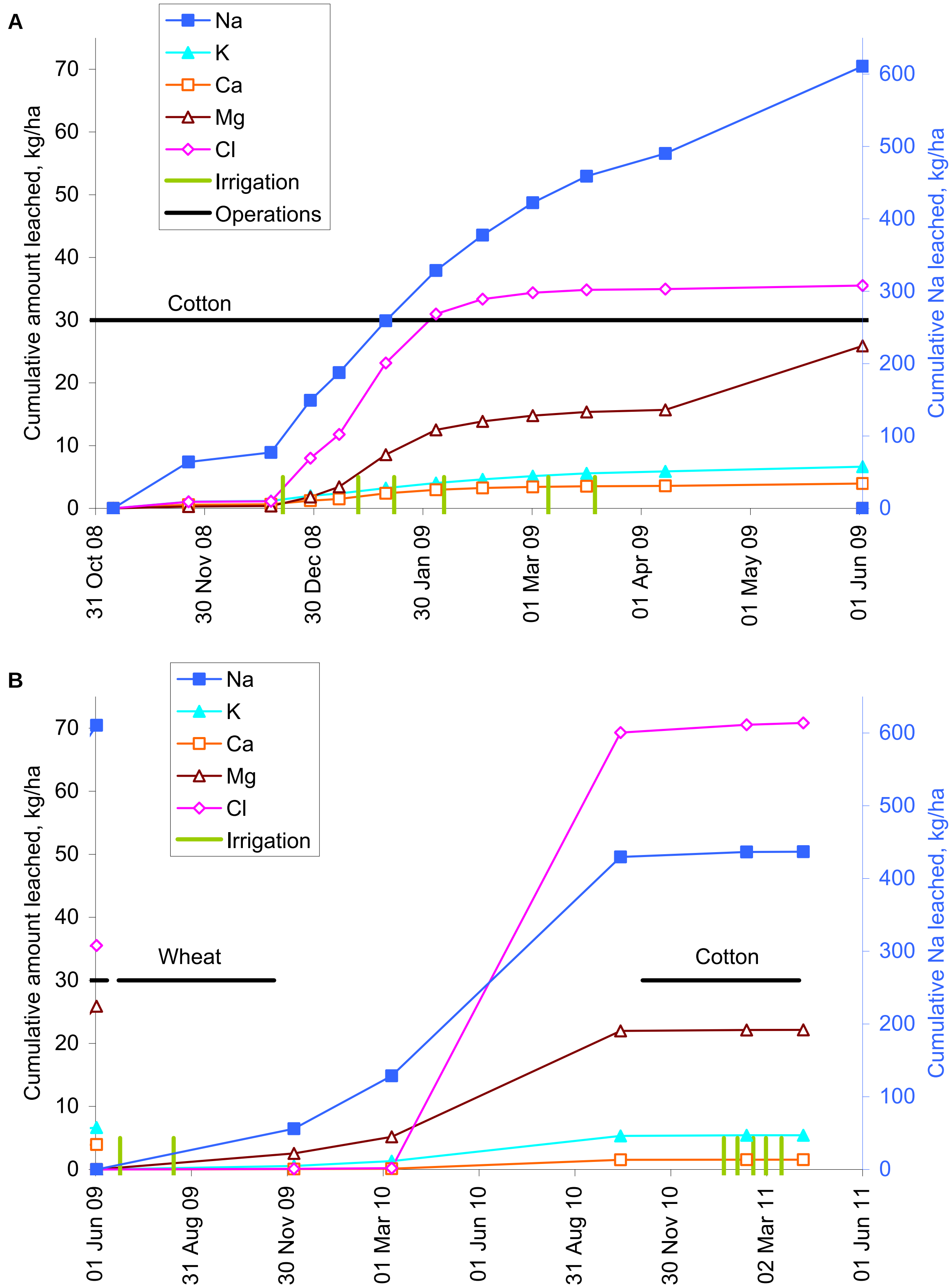

Figure 23. Cumulative amounts of various cations and Cl leached from the profile A) during the 2008/09 cotton season and B) during the 2009 wheat, 2009/10 fallow and 2010/11 cotton seasons. Na shown on the right vertical axis, other ions on the left.

The behaviour of Mg requires further investigation.

In summary the chemical signature of the drainage seems to oscillate between two patterns:

- High EC: high Na and K, and low Cl and Ca indicating flow dominated by water moving through the matrix.
- Low EC: low Na and K, and high Cl and Ca indicating flow dominated by-pass flow and more closely reflecting the chemical signature of the irrigation water.

There is possibly a third pattern:

- High EC: high Na and K, and high Cl and Ca (found when the wetting front passed tray depth in September 2010) indicating a mix of flushing through the matrix and more rapid flow from the surface. In this case the two sources might be more evenly balanced unlike during the irrigation season.

The cumulative leaching of each ion over the season are shown in Figure 23. The leachate was dominated by sodium, of which over 600 kg/ha was leached over the 2008/09 cotton season and 435 kg/ha over the subsequent period. The input of sodium in irrigation water over these two periods was 237 and 492 kg/ha, respectively. (The sodium content of the irrigation water used for the 2009 wheat crop was much greater than normal, 110 mg/L, because a greater proportion of it was sourced from groundwater rather than river water). As a result there was a net export of sodium during the 2008/09 cotton season, but a net accumulation during the subsequent period (Table 6). The other ions accumulated over the same two periods showing that the inorganic chemistry of the soil is continuously changing in response to inputs of salts in irrigation water.

Table 8. Inputs from irrigation and exports with leachate of various ions during the 2008/09 cotton season and the subsequent period from 2009-11.

		Cl kg/ha	Na kg/ha	K kg/ha	Ca kg/ha	Mg kg/ha
Cotton 2008/09	Irrigation input	121	237	30	157	76
	Leachate	36	610	7	4	26
	Net accumulation	86	-374	23	153	50
2009-11	Irrigation input	141	492	26	178	94
	Leachate	71	437	5	2	22
	Net accumulation	70	55	20	177	72

4.4.2 Nitrogen

The potential for drainage to leach nitrogen from the profile is of importance because it can reduce fertilizer efficiency and can pollute groundwater. The concentration of nitrate N in the drainage for the 2008/09 cotton season onwards is shown in Figure 24. During the cotton season concentrations rose to 35 mg/L after the first irrigation before decreasing over the rest of the season. The early peak occurred because this was when N was most available since it was applied at sowing. The fact that it appeared in the drainage at 2 m so quickly was due to it being transported by by-pass flow out of the root zone. The concentration similarly rose during the 2010/11 cotton season, but the lack of drainage volume meant it was collected only twice so that drainage from different parts of the season were mixed together.

When the N concentration is combined with the drainage volume to show the absolute amount of N leaving in drainage though the season (Figure 25) it is apparent that the majority of the N that was leached did so after the first four irrigations, with a total of 9.5 kg/ha being leached through the entire season. This represents 6% of the 160 kg N/ha applied to the crop (60 kg N/ha at sowing and 100 kg N/ha in December, both applications as urea). The very low drainage during the subsequent period resulted in only 0.3 kg/ha being leached (not shown).

These results clearly point to the importance of avoiding drainage early in the season as it is when N is most available. N was not measured during the 2006/07 cotton season, when the crop was irrigated much earlier than in 2008/09 or 2010/11. It is interesting to speculate that N losses might have been much greater during that season.

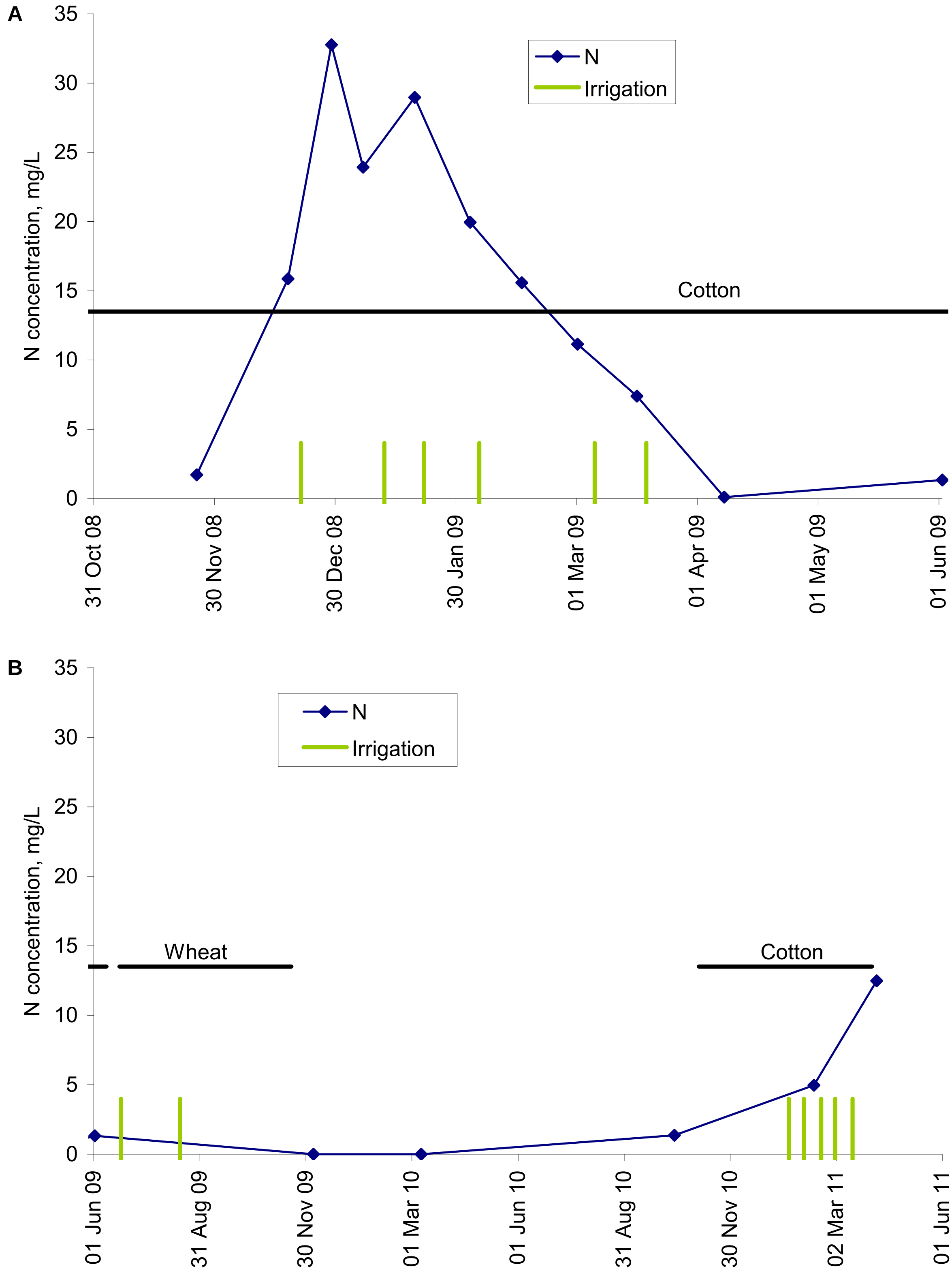

Figure 24. Concentration N (as NO_3^-) in drainage water A) during the 2008/09 cotton season and B) during the 2009 wheat, 2009/10 fallow and 2010/11 cotton seasons.

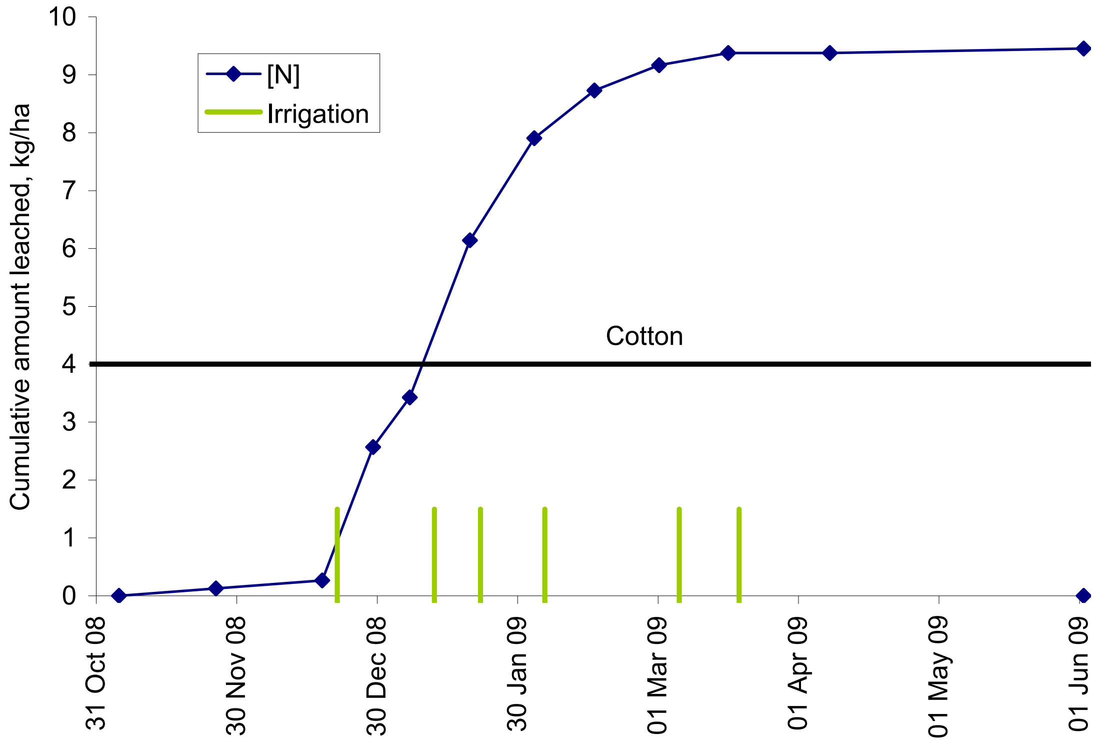

Figure 25. Cumulative amounts N (as NO_3^-) leached from the profile during the 2008/09 cotton season.

4.5 Groundwater

4.5.1 Hydrogeology

The alluvial sediment units of the Lower Namoi River catchment described in many previous studies correlated well with the stratigraphy intercepted by the boreholes at the lysimeter site.

The Narrabri Formation is the uppermost of these units, extending to depths of as much as 40 m. It predominantly consists of clay with minor, lens-shaped sand and gravel beds deposited by prior streams. Extensive sandy sediments have also been reported below the clay. Groundwater aquifers in this unit are unconfined or semi-confined and are not used for irrigation due to their high salinity and low yield. These aquifers are recharged primarily through surface infiltration from river channels, flood events, rainfall and irrigation.

Underlying this is the Gunnedah formation which is up to 80 m thick, consisting predominantly of well sorted sand and gravel with sequences of minor clay beds. The aquifers in this unit are typically confined, with good yield and water quality and are extensively used for irrigation. This formation is recharged not only by leakage from the Great Artesian Basin, but can also be from upper aquifers where clay sequences are insufficiently thick or continuous to act as aquitards, or where hydraulic gradients through aquitards are downward, such as when abstraction has reversed formerly upward gradients.

Large palæochannels at former river alignments are also present within these formations, containing granular bedload deposits ranging from gravelly sand to fine sand, often interbedded with thin layers of silt to clay size sediment. The palæochannels can be up to tens of metres deep and can provide connection between surface water and aquifers.

The two site bores were drilled using the mud rotary drilling method. This method does not provide discrete soil samples suitable for particle size or chemical analysis due to the soil disturbance, fracturing of large aggregates and mixing of cuttings with the drilling fluid, but the drill cuttings do provide a relative indication of changes in texture and colour with depth.

The nominal soil stratigraphy at piezometer P1 consisted of 4 m of clay overlying 7 m of silt and clay. This was underlain by the water table aquifer beginning at 11 m bgs (below ground surface), comprising 8 m of sand over 5 m of gravel. The borehole was completed at 24 m depth, where the gravel became silty. The piezometer was screened from 20 to 21 m bgs. The standing water level on 01 September 2006 was 14.50 m bgs.

Piezometer P2 was installed in a separate borehole from P1, rather than nesting the casings in a single borehole. This avoided possible annular leakage between aquifers through seals as the available casing diameter was large relative to the bored diameter. Although the P2 borehole was only 5 m from P1 there were stratigraphic differences over the duplicated depth.

P2 intercepted 7 m of clay over 1 m of silt and clay. Below this, the top of the watertable aquifer was encountered at a shallower depth – 8 m bgs – and consisted of interbedded layers of silt, sand and gravel to a depth of 23 m bgs. This was underlain by a 9 m thick aquitard of silt and clay with interbedded sand and gravel layers. Below this the confined aquifer was encountered at 32 m bgs, consisting of gravel and sand to 37 m bgs. The borehole was completed in clayey sand at 38 m bgs. The piezometer was screened from 34 to 35 m bgs. The standing water level on 01 September 2006 was 17.75 m bgs.

4.5.2 Groundwater responses

The piezometer water level loggers recorded absolute levels: the sum of the barometric pressure and the depth of water above the sensor measurement point. Sensor gauge levels were obtained by subtracting barometric pressures, in water column equivalent, from the absolute levels. Total heads were calculated as the sum of the absolute sensor levels plus the elevation of the site; hydraulic heads as the gauge sensor levels plus the measurement point elevation. The vertical hydraulic gradients between piezometers were calculated as the difference in total head elevations divided by the difference in screen elevations. Hydraulic heads were not used to determine hydraulic gradients due to errors at low gradients. Standing water level (SWL) measurements are reported as depth below ground surface (bgs).

In the vertical dimension, watertable levels are the net sum of water inputs and outputs, from above and below the aquifer. Deep drainage out of the root zone migrates as unsaturated flow through the vadose zone and can, ultimately, recharge the watertable.

The unsaturated flow rate is dependant on the unsaturated hydraulic conductivity and soil tension gradients, both of which vary non-linearly in relation to the water content and particle size distribution of the soils. The differing soil strata textures and the changing water contents result in considerable variation in rates of unsaturated flow through the vadose zone.

Leakage between the water table and confined aquifers occurs as saturated flow through the interlaying aquitard. The rate of this flow is directly proportional to the vertical hydraulic gradient between these aquifers and the effective saturated hydraulic conductivity of the aquitard materials. While the aquitard hydraulic conductivity is constant, the hydraulic gradient can vary considerably in both magnitude and direction, with upward, downward or zero leakage possible.

P1 hydraulic heads in the watertable aquifer ranged from 183.350 to 184.027 m (SWL of 15.970 – 16.650 m bgs) during the measurement period (Figure 26). The aquifer was partially saturated with levels approximately 5 to 6 m below the top of the 13 m thick sand and gravel aquifer. Water levels decreased to below sensor depth in September 2009, but it is unlikely they would have decreased significantly below the measured minimum or approached the base of the aquifer considering previous decline rates and levels measured following sensor repositioning.

P2 hydraulic heads in the confined aquifer ranged from 177.904 to 182.688 m (SWL of 17.312 – 22.096 m bgs) during the measurement period (Figure 26), which is above the top of the aquitard meaning the aquifer is confined. However, levels were briefly below sensor depth during September and December 2009, during which they were possibly below the top of the aquitard at 23 m bgs, although it is unlikely levels reached the bottom of the aquitard at 32 m bgs.

Vertical hydraulic gradients ranged from +0.070 to +0.392 m H_2O/m during the measurement period, where positive gradients indicate a downward direction (Figure 26). The gradients were dominated by the much more dynamic head fluctuations in the confined aquifer. The consistently downward vertical hydraulic gradients result in continuous movement of saline water from the watertable into the confined aquifer. This is of concern due to its potential to contaminate the P2 aquifer which is used for a variety of agricultural and other enterprises.

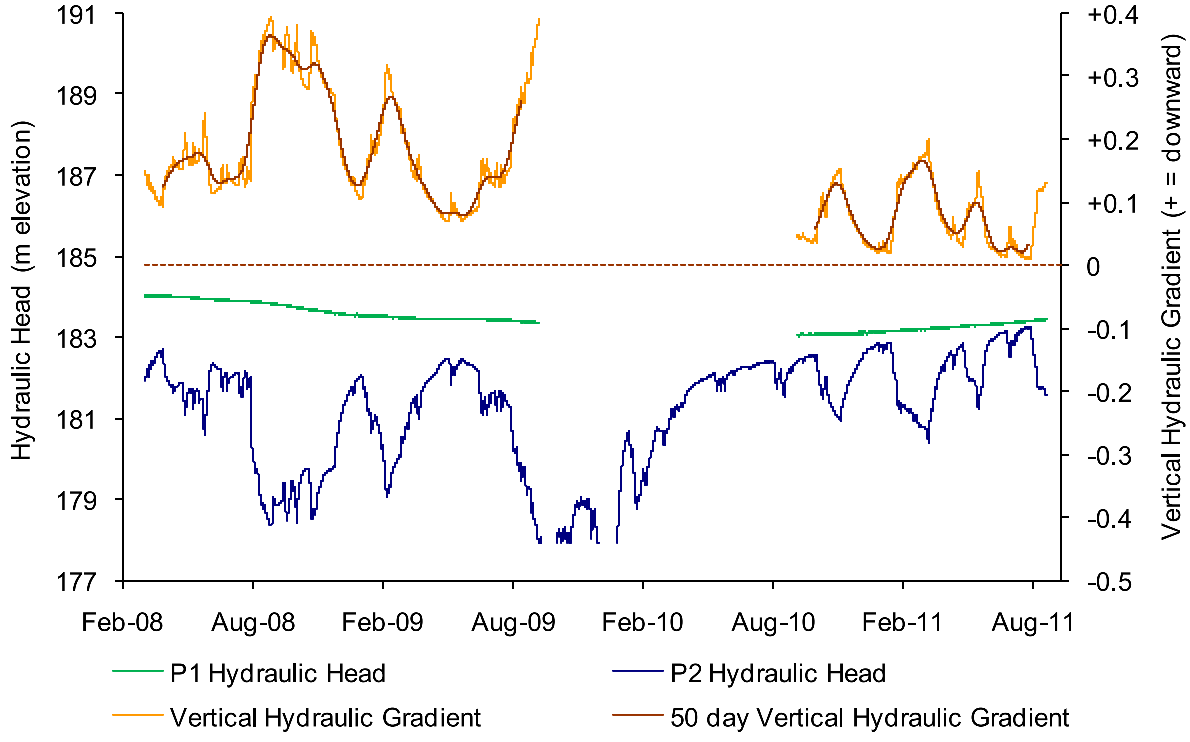

Figure 26. Hydraulic heads in the P1 and P2 piezometers at the ACRI lysimeter facility from February 2008 to August 2011. Also shown is the hydraulic gradient between the two aquifers.[1]

1 The smoothed hydraulic gradient data were generated by applying a low pass, least square filter with a 50 day window at the minimum frequency of 0.02 cycles per day (cpd) or 2.3x10-7 Hz. This filter provided the greatest correlation of the damped vertical hydraulic gradient with the rate of change of water table head. The hourly rate of change of P1 hydraulic head was calculated within a moving, centred 2 h window after first removing the short period fluctuations with this same low pass filter.

The large head fluctuations of the confined aquifer (P2) were caused by pumping from local irrigation bores, of which three were less than 3 km from the piezometer. Local irrigation bores have typically been installed with screens across each sand and gravel layer between the uppermost confined aquifer and their completed depth. One of these is the ACRI irrigation bore, located 1.97 km SSE of the piezometers. Its pump is usually operated only during daylight hours. P2 levels respond to pumping from this bore within a few hours of activation, generating responses of less than 0.2 m (Figure 27). Other bore pumps on adjacent, commercial farms are typically operated continuously for multiple days resulting in overall responses of several metres during these periods.

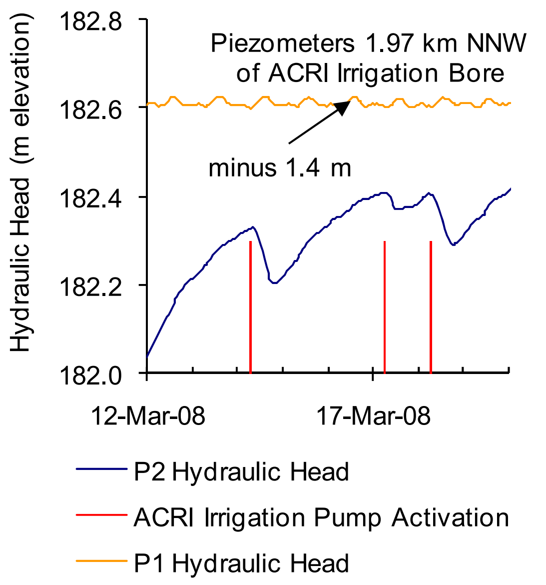

Figure 27. Detail of hydraulic heads in the P1 and P2 piezometers during March 2008, showing the effect of pumping from the ACRI bore.

P1 water table levels did not exhibit short term responses to these pumping events as the fluctuations of the confined aquifer were damped out by the aquitard. The trend in P1 levels was of long term variations of small magnitude. P1 levels exhibited a net decline of less than 0.8 m over the18 months from February 2008 to August 2009 (Figure 26). Between September 2010 (when the sensors were repositioned) and August 2011 it rose by less than 0.5 m. The decline during 2008/09 was because discharge from P1 to P2 due to the downward gradient was not matched by recharge from above. The lack of recharge may have been due to the decline of water use for irrigation during a period of drought as well as lower rainfall. Similarly the P2 aquifer showed an overall downward trend over this period, probably due to increased pumping to make up for a shortfall in surface water for irrigation. The decline in P2 heads increased the gradients which would have further increased downward leakage from the P1 aquifer.

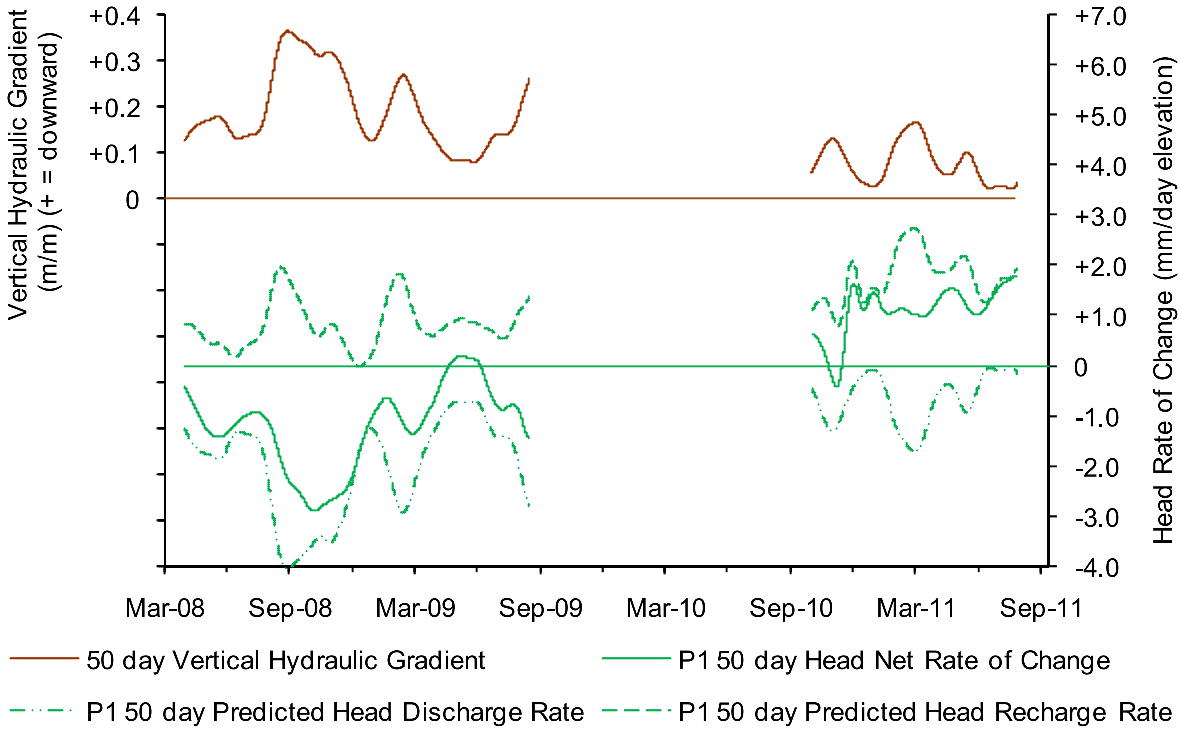

Figure 28. The hydraulic gradient between the upper, watertable aquifer and the lower, confined aquifer over the measurement period (top) (see also Figure 26), and the measured rate of change in the head of the upper aquifer (bottom). The dashed lines are the estimated rate of discharge from the upper to the lower aquifer and the estimated recharge rate into the upper aquifer from the vadose zone.

4.5.3 Estimating watertable recharge

The rate of saturated flow rate through the aquitard is directly proportional to the vertical hydraulic gradient. The vertical hydraulic gradient negatively correlates with the rate of change of the hydraulic head (P1) of the watertable when the watertable recharge rate from deep drainage through the vadose zone is in steady state. When the watertable recharge rate is zero and the hydraulic gradient is downward, the rate of change of the watertable is equal to the discharge rate through the aquitard, assuming negligible lateral flows through the watertable aquifer.

To partition the upper aquifer discharge rate from the net rate of change (i.e. the measured rate of change), the vertical hydraulic gradient was linearly regressed against the rate of change of the measured hydraulic head over a 15 day period (5-20 December 2008) immediately prior to the first irrigation of the 2008/09 cotton season. During this period deep drainage at lysimeter depth had been at or near zero during the preceding month and the assumption was made that recharge to the watertable (P1) from the vadose zone was zero. Thus over this period the rate of change of P1 head should have been directly proportional to the vertical hydraulic gradient. The resulting regression relationship was then applied to the vertical hydraulic gradient over the entire period (except where P1 or P2 heads were missing) to estimate the discharge rate from the P1 aquifer to the P2 aquifer. The difference between the measured rate of change of P1 and the estimated P1 discharge rate can be used as an estimate of the recharge rate into P1 (Figure 28).

However, the units of this recharge rate are millimetres of elevation per day, whereas rainfall, irrigation and lysimeter drainage consider the volume of water (expressed as volume per unit area, i.e. depth) and have units of millimetres of water per day. The ratio of former to the latter relates to the formation's porosity (specific yield). The recharge rate in millimetres of water per day was calculated using a range of specific yield values typical of the granular aquifer soils encountered, as shown in (Figure 29). The value used for specific yield causes the estimate of recharge to vary by up to ±0.15 mm water/day.

Recharge rates into P1 from the vadose zone estimated using this method varied from 0 – 0.7 mm/day using an assumed specific yield of 0.25 (Figure 29). The drainage rate at 2.1 m bgs measured by the lysimeter is shown for comparison in Figure 30. For this figure the drainage rate has been smoothed using the same 50 day window used to smooth the vertical hydraulic gradient between P1 and P2. The peak drainage rates are therefore much less than discussed in Section 4.1.3, because they are averaged over a longer period. The greater smoothing is useful for comparison with the estimated recharge rate at 16 m bgs since the latter is much more damped than drainage at 2 m bgs. First, the short-term variations in drainage in response to individual irrigation or rainfall events are averaged out. Second, the recharge at 16 m bgs averages the drainage over a much larger area, that includes not only the lysimeter plot, but possibly also the roadways, irrigation channels and parts of neighbouring paddocks. Third, the soil of the vadose zone provides a large soil water storage capacity that may exhibit response periods much longer than even the observed seasonal trends in drainage and aquifer recharge.

The seasonal peaks in recharge resemble the peaks in seasonal drainage. There is a seasonal drainage peak of 0.7 mm/day from the 2008/09 cotton season on 20 January 2009, which corresponds to a peak in recharge of 0.46 mm/day on 4 February – a delay of 15 days. A second drainage peak of 0.16 mm/day on 5 May 2009, possibly due to rain late in the 2008/09 cotton season, corresponds to a broad recharge peak of 0.22 mm/day 5 days later. Caution is required in attributing causal relationships between peaks in drainage over 1.58 m^2 at 2 m bgs with peaks in recharge at 16 m bgs, affected by water movement through the vadose zone over an unknown, but much larger area. However, the correspondence is striking.

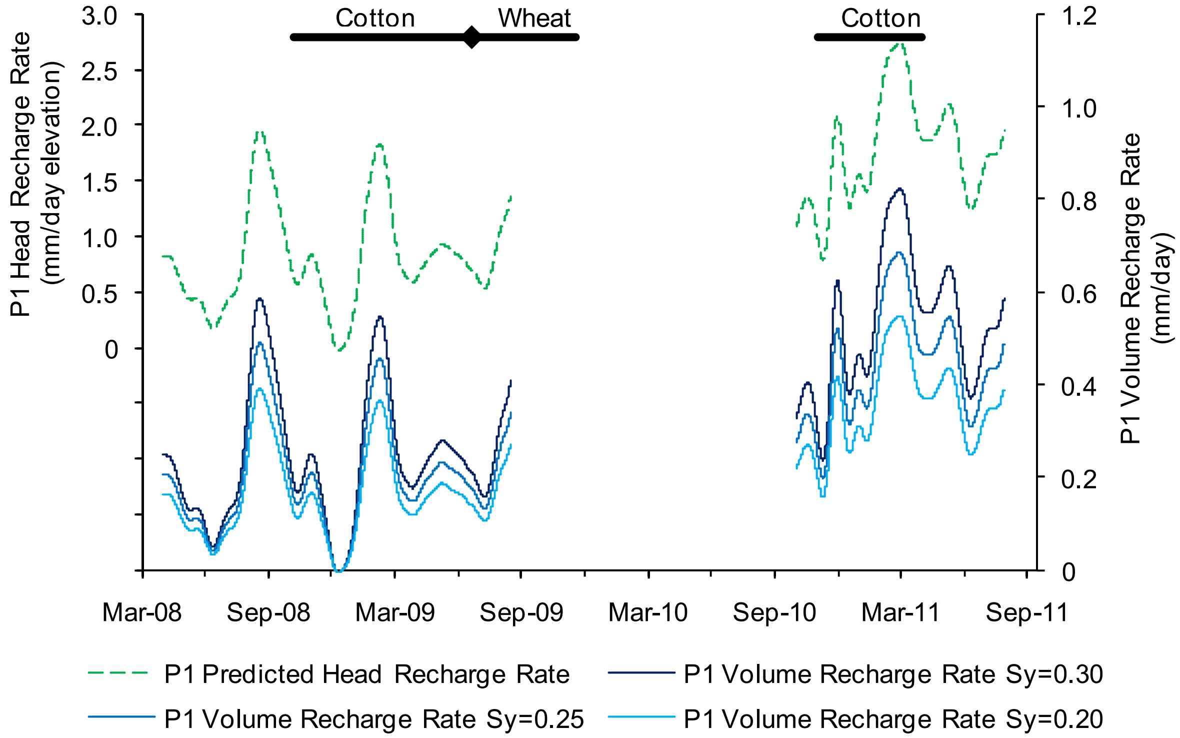

Figure 29. Estimated recharge rate into P1 from the vadose zone in units both of mm head/day (left axis) and mm water/day using different values of specific yield for the P1 aquifer (right axis).

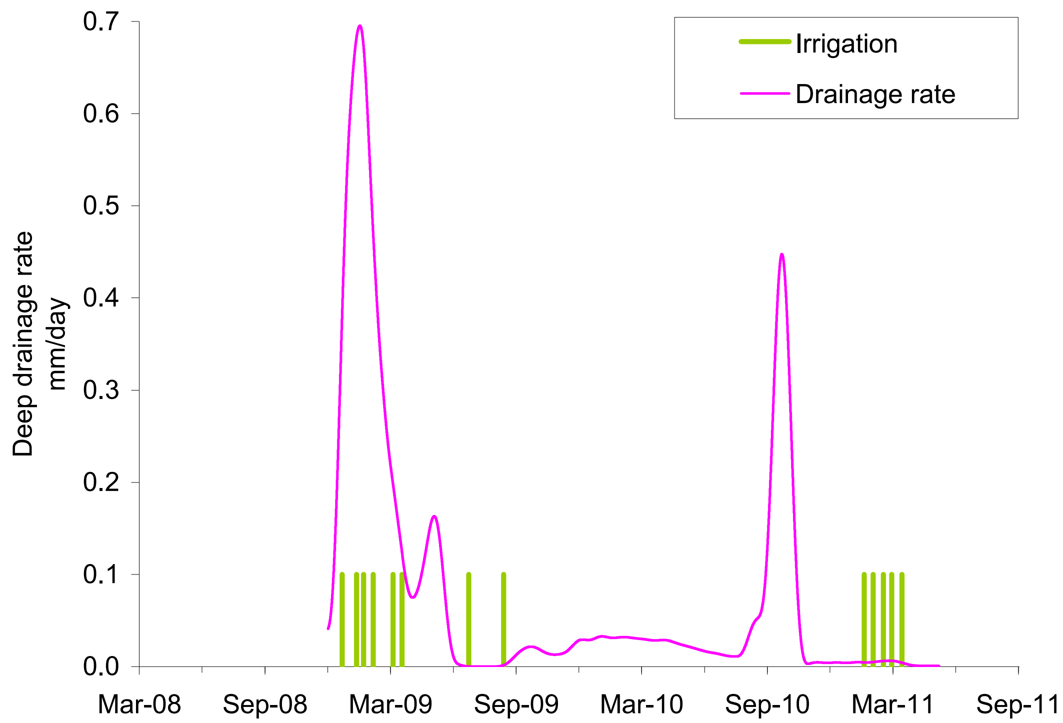

Figure 30. Drainage rate at 2.1 m bgs measured by the lysimeter. The rate has been smoothed using a 50 day window – the same as used for the vertical hydraulic gradient between P1 and P2. This is much greater smoothing than the 24 hour window used in Figure 12 to Figure 14 and gives much lower drainage rates and many fewer peaks. However, the total drainage calculated over time remains the same.

There is a similar correspondence between a drainage peak of 0.45 mm/day on 23 September 2010, caused by a wetting front due to rain during the fallow period, and a recharge peak of 0.34 mm/day 26 days later. This is followed by two recharge peaks of 0.52 and 0.69 mm/day on 1 December 2010 and 1 March 2011 respectively, for which there are no corresponding drainage peaks. As discussed in Section 4.1.3, there may have been localized compaction near the lysimeter, so that, whilst the drainage recorded by the lysimeter over the 2010/11 cotton season was negligible, drainage further from the lysimeter might have been greater (as predicted by the model proposed in Section 4.2) with a corresponding increase in recharge as in the 2008/09 season.

Together with these peaks there was a background level of recharge that appeared to be reasonably stationary during the first measurement period but steadily rising during the second. The background recharge may reflect recharge trends over a wider area or it may reflect trends in the water content of the vadose zone and their impact on its conductivity.

In summary, an attempt has been made to estimate recharge under the lysimeter at 16 m bgs. Whilst there is some correspondence between seasonal drainage measured by the lysimeter, the aquifer averages recharge over a much larger area than the lysimeter. Until a longer record of drainage and recharge are obtained, it will be difficult to determine or understand a relationship between drainage and recharge.

5. OUTCOMES

Improved quantification and understanding of drainage under irrigated cotton on heavy clay soils

- Drainage has been quantified for three cotton seasons, a wheat season and a fallow. Drainage under cotton varied from 0 – 74 mm. Under the wheat crop it was negligible, but was 23 mm under fallow. Drainage for the complete rotation from 2008/09 cotton, 2009 wheat and 2009/10 fallow was 77 mm.

- Two types of drainage occurred on the heavy clay soil at the ACRI lysimeter:
  - Drainage through the soil matrix when a wetting front passes out of the root zone.
  - Drainage due to by-pass flow after furrow irrigation.

- Matrix drainage occurs after prolonged rainy periods and involves the whole profile being wet from the top down until the wetting front passes out of the root zone, which may take many months.
  - Drainage rates may be low (e.g. 0.5 mm/day), but can be sustained over long periods (e.g. a month).
  - Drainage moves through the soil matrix and is effective at flushing out salts that have been added by irrigation and concentrated by ET. Such drainage has relatively high EC of >5 dS/m.
  - The amount of rainfall required to produce drainage depends on the soil water deficit of the soil profile. The greater the deficit, the more rainfall required to produce drainage. The wetting front that caused drainage in September 2010 required 640 mm of rain over 9 months to fill a 200 mm soil water deficit before it caused drainage (with 70% of the rain being leaving as ET).

- By-pass drainage occurs because 'free' water is added to the surface and flows rapidly down macropores without necessarily wetting the subsoil. In addition, hydraulic gradients in the matrix can be still be upwards.
  - Drainage rates increase rapidly after irrigation, peaking after only 25 hours. Peak rates can be >3 mm/day. After peaking the rate declines exponentially over a week to about 0.5 mm/day. Heavy rain during the irrigation season can induce a similar response.
  - Drainage has less contact with the soil matrix and is less efficient at flushing salt from the profile. Hence its EC is generally lower, from 2 to 3 dS/m.

- Whether irrigation triggers by-pass flow drainage and how much it produces, depends on the soil water deficit before the irrigation.
  1. Irrigation almost fills the deficit in the top 0.5 m of soil, although air-entrapment leaves about 20 mm empty.
  2. Irrigation also fills about 50% of the deficit between 0.5 and 1.0 m depth
  3. However, more irrigation infiltrates than is accounted for by the change in water content of the top 1 m. The extra travels through 1 – 2 m depth with only a small amount being absorbed by the soil and the remainder becoming drainage. The amount of 'extra' irrigation and therefore the amount of drainage tends to increase with increasing deficits between 0 – 0.5 m, but tends to decrease with increasing deficits between 0.5 – 1.0 m. However, this relationship is only weakly established at present and requires further study before it can be confirmed.
- Compaction can reduce drainage to zero, but is clearly undesirable for crop growth.

- The greatest risk of drainage occurring after irrigation is when the soil is dry from 0 – 0.5 m depth but wet from 0.5 – 1.0 m. This is most likely to occur early in the season before crop ET is extracting much water from 0.5 – 1.0 m. If irrigation is required early in the season due to a lack of rain, the 0.5 – 1.0 m layer is wet up after one or two irrigations, triggering large drainage rates after subsequent irrigations. The risk is even greater if the subsoil has already been wet before the cotton season. Conversely, as the season progresses and the crop creates progressively larger deficits from 0.5 – 1.0 m, so the amount of drainage decreases.

Improved modelling of the soil water balance under irrigated cotton

- Predicting drainage using water balance modelling as part of a crop growth model can help devise strategies to improve water use efficiency and decrease the overall amount of drainage.

- The soil water behaviour that generates matrix drainage conforms to conventional soil physics understanding, and can be adequately simulated using existing water balance models, of both the Richard's equation type or the tipping-bucket type.

- Soil water behaviour that generates by-pass flow drainage cannot be predicted using existing models. An empirical model has been developed to predict the amount of drainage in the 48 hours after irrigation. However, it relies on only three seasons data and predictions have high uncertainty. Improvement of this model with more data, would allow it to be incorporated into an existing water balance model so that by-pass flow drainage can be predicted for a range of scenarios.

Assessment of alternative, less expensive methods for estimating deep drainage

- The barrel lysimeter installed next to the ACRI tension lysimeter overestimated drainage by 48% over the 2006/07 and 2008/09 cotton seasons. However, detailed comparison during the 2008/09 season showed the barrel lysimeter grossly overestimates during larger events, but failed to record any drainage during smaller events. The most likely reason for the former was the persistence of the effects of soil disturbance during installation. The reason for the latter was that vacuum applied to the base of the barrel lysimeter was insufficient to extract the drainage that had collected in the base of the barrel before it was extracted by the dryness of the surrounding soil.

- The chloride mass balance method for estimating seasonal drainage was found to underestimate drainage by 55% during the 2006/07 and 2008/09 cotton seasons. The results were not comparable for the 2010/11 season due to suspected localized compaction over the lysimeter. The underestimation results because the method assumes that water moves as a wetting front through the soil so that inputs of chloride in the irrigation water are captured by the soil matrix. Where there is substantial by-pass flow, the assumption no longer holds true because a) some of the chloride by-passes the soil matrix and b) the chloride already in the soil matrix is not mobilized in the way it would be if water was moving through the soil matrix.

Improved understanding of nitrogen losses in drainage

- During the 2008/09 cotton season 9.5 kg N/ha was leached by drainage (as nitrate), representing 6% of the N applied. Concentrations of N in drainage were greatest earlier in the season when N was most available. Most N was lost in drainage after the first four irrigations, when drainage was dominated by by-pass flow.

- N losses through drainage can be minimized by a) avoiding irrigation early in the season when drainage can be high (as in 2006/07) and b) splitting N applications so that a greater proportion is applied once the risk of drainage is lower due to more substantial soil water deficits being developed in the 0.5 – 1.0 m layer between irrigations.

Improved understanding of links between drainage and groundwater recharge

- The watertable aquifer is unconfined and at about 16 m below ground surface (bgs). The watertable rises and falls very slowly in response to long term changes in recharge and the downward hydraulic gradient to the confined aquifer below. The aquifer is quite saline and not extracted by pumping.

- The next aquifer down is confined and had a head between 17 and 20 m bgs. The head fluctuates between this range in response to groundwater pumping. This aquifer is good quality and is extracted for a variety of economic uses.

- The hydraulic gradient between the aquifers is downwards. This means that there is a slow leakage of salty water downwards into the good quality aquifer. The rate of leakage increases as the head of the lower aquifer is drawn down by pumping, or as the watertable head increases due to recharge from drainage exceeding leakage rates.

- The estimated recharge rate into the upper aquifer is 0.0 – 0.7 mm/day. There was a strong correlation between seasonal peaks in deep drainage from the root zone and peaks in the recharge rate, with the recharge peaks occurring 1 to 4 weeks later. The drainage peaks were caused both by irrigation and by wetting fronts moving through the soil profile after prolonged rainy periods. However, only three pairs of peaks have been examined, so definitively establishing a link between drainage peaks and recharge peaks requires further monitoring.

- There also appears to be a level of background recharge that increases and decreases on a seasonal timeframe. Establishing the level of background recharge and whether it is due to the overall wetness of the vadose zone (which affects its conductivity) or simply the drainage over a wider area requires developing methods to determine the wetness of the vadose zone.

6. CONCLUSIONS

The ACRI lysimeter facility has provided unprecedented detail about the nature of deep drainage in heavy clay soils under furrow irrigated cotton. It has shown that drainage under cotton can be significant and occurs in two forms – matrix drainage and by-pass drainage. The former is the ‘normal’ form of drainage and is generally well understood and modelled. It occurs whenever the soil profile is filled to capacity by periods where water inputs exceed losses by ET. This can occur for example during prolonged rainy periods during a fallow, when ET is at its lowest. If irrigation occurs when the subsoil is already wet there is also potential for this type of drainage. Minimizing this type of drainage requires a risk management approach, since some drainage is inevitable, and indeed desirable in order to prevent the build up of salt. Risk management involves the whole cropping system – not just the cotton crop.

- Measures to minimize the risk of matrix drainage essentially mean maintaining sufficient soil water deficit to contain likely inputs of water through rain or irrigation. Measures can include optimizing the deficit used to trigger irrigation and manipulating the crop rotation to ensure the maximum possible subsoil deficit before fallow periods or the irrigation season.

The other type of drainage occurs as rapid flow down macropores and by-passes the soil matrix. This type of drainage is likely to be more difficult to manage because it occurs despite the presence of a subsoil deficit and even in the presence of upward hydraulic gradients. There are indications that by-pass drainage is to some degree controlled by interactions between the deficit from 0 – 0.5 m and that from 0.5 – 1.0 m. Drainage tends to increase as the 0 – 0.5 m layer gets drier, possibly due to greater cracking. However, drainage appears to decrease as the 0.5 – 1.0 m gets drier, even though irrigation only fills about half its deficit.

- The greatest risk of by-pass drainage is when early irrigation (e.g. before December) is required due to lack of rain. In this situation, the subsoil wets after the first one or two irrigations, and subsequent irrigations cause large amounts of drainage. Conversely, irrigations later in the crop, when large subsoil deficits build up between irrigations, reduce drainage to much lower levels.

Leaching salt from irrigation water that has accumulated in the soil is the reason why some drainage is necessary. However, by-pass drainage is less effective at leaching than matrix drainage. Greater understanding is required about the how rapidly salt builds up in the profile in the light of by-pass drainage. Long-term modelling should be used to determine the frequency of matrix drainage and whether the frequency is sufficient to prevent salt build up. The results also demonstrate that the inorganic chemistry of the profile is continually changing with different cations showing different patterns of net accumulation or leaching in different seasons. The changes are likely to be in response to the overall balance of irrigation versus rainfall as well as the source of irrigation water and the existing concentrations of salts in the soil profile.

The lysimeter allowed the leaching of nitrate to be measured. Losses of nitrate are greatest early in the season when N is most available and drainage is greatest because of the lack of subsoil deficit. In 2008/09, N equivalent to 6% of the applied fertilizer N was lost in drainage. Because it is transported by by-pass flow it is not simply moved deeper in the profile where it can still be extracted by plants, but transported out of the profile in drainage.

- Minimizing N losses in drainage could involve more use of split fertilizer applications, so a greater proportion of N is applied once drainage rates have reduced.

Assessment of alternative, less expensive methods of measuring drainage has been disappointing. Such methods would allow drainage to be estimated under a much wider range of soil type × climate × cropping system combinations. The barrel lysimeter method appears to over estimate drainage whereas the chloride mass balance method underestimates it.

Detailed monitoring of the two piezometers that are part of the lysimeter facility has shown that watertable recharge at 16 m below ground surface varies between 0 – 0.7 mm/day and may be responsive to drainage at 2 m depth. The results are still tentative and confirmation requires analysis of data from a longer monitoring period. In summary:

- Drainage at 2 m depth can begin to arrive at the watertable 16 m below ground surface within a matter of weeks.

- There is continuous downward leakage of salty water from the upper aquifer into the next one from which water is extracted for a variety of uses. The leakage is exacerbated by the drawdown created by groundwater pumping and by rising watertables from excess drainage.

7. EXTENSION OPPORTUNITIES

The results of this project are of importance to both cotton growers and those responsible for natural resource management. The finding that most drainage during the irrigation season occurs as by-pass flow has implications both for reducing drainage and for the efficient leaching of salt from the profile, making both more difficult to manage. The loss of nitrogen in drainage, whilst relatively small, is reducible by improved management practices. In addition, the fact that the watertable is still relatively deep in the irrigation areas along the Namoi, should not lead to complacency. It appears that deep drainage is leading to relatively quick responses in the recharge rate into the upper aquifer and that leakage of salty water is occurring between the upper aquifer and the next aquifer down from which water is extracted for a variety of purposes.

There is potential for packaging the findings of this research to aid growers better understand the major drivers for drainage, its dangers and some steps that might be taken to reduce the risk of excessive drainage.

The ACRI lysimeter facility has monitored soil water conditions and drainage under irrigated cotton, as well as groundwater, in much greater detail than before. The data has provided new understanding of how drainage occurs and the roles of by-pass flow and antecedent water content. Continuing monitoring into the future over long periods will confirm and refine the understanding gained to date. The results to date allow identification of areas for future research using the lysimeter. These include experiments to close the nitrogen balance, given the importance of N both economically and as a precursor of greenhouse gas. Such experiments should ideally involve monitoring N losses via drainage using the lysimeter, atmospheric N losses using chambers and the use of N^{15} isotope to allow the tracing of a particular N application as it passes through the soil-plant-atmosphere system. Experiments that monitor the EC and inorganic chemistry at more frequent intervals than used to date, combined with measurements of soil inorganic chemistry through the profile, would allow greater understanding of by-pass flow and of the way salts are stored in and leached from the profile. The use of an inorganic tracer such as bromide would be invaluable for this.

The aim of any future monitoring and shorter-term experiments must be to develop system understanding that can be applied, most likely through the use of simulation modelling, to a wider range of soils, management practices and climates than represented at the lysimeter. This would require design of a measurement programs that could be carried out on a much wider variety of situations in order to verify such models.

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