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Part 1 - Summary Details

Please use your TAB key to complete Parts 1 & 2.

CRDC Project Number: CLW1301

Project Title: Measuring deep drainage from a cotton/wheat trial

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Part 3 – Final Report

(The points below are to be used as a guideline when completing your final report.)

Background

1. Outline the background to the project.

1.0 DEEP DRAINAGE

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 cause loss of nitrogen from the root zone by leaching.
- Nutrients, salts and agrochemicals leached by deep drainage are a source of contamination if entering groundwater.
- Deep drainage and salt mobilisation is increased under land cleared of native vegetation for irrigated agriculture in arid and semi-arid climates and can lead to rising water tables, waterlogging, saline river discharges or soil salinity

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.

2.0 DRAINAGE MEASUREMENT

2.1 Equilibrium Tension Lysimeter

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) and other components of the water balance. The facility acted as a benchmark against which two less expensive methods of estimating drainage were tested:

Drainage previously measured by the lysimeter under cotton varied from 0 to 74 mm per season in the three seasons of measurement. Drainage under a single wheat crop was negligible and 23 mm of drainage was measured during the fallow. The greatest drainages occur when early season irrigations are applied to fill shallow soil water deficits over wet subsoils.

Drainage was found to occur in two distinct ways, matrix flow and by-pass flow. Matrix drainage occurs as top down wetting through the soil profile, with low drainage rates over long periods but with effective leaching of salts. Bypass drainage occurs as free water flowing rapidly through soil macropores; can be unaffected by the hydraulic gradients of the matrix and has much lower leaching efficiency than matrix drainage.

2.2 Water Balance

Drainage can be estimated by measuring or calculating all other components of the water balance (e.g. Ringrose-Voase et al. 2003), and drainage assumed to be the remainder. However, the drainage component of the water balance is a very small term relative to the other water balance components. The risk in this method is that the errors in the other water balance component measurements can be of the same order of magnitude as the drainage term itself.

2.3 Chloride Mass 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 chloride mass balance method (in collaboration with N. Hulugalle, NSW Department of Industry and Investment) was found to underestimate drainage by 52% compared with the equilibrium tension lysimeter. This is due to the method's assumption that water moves as a uniform front through the soil, moving chloride with it. However, under 'by-pass' conditions some water applied to the surface will 'by-pass' the soil matrix and flow through macropores, not effectively mixing with soil solution in the matrix. This leads to underestimation of drainage. However, the ability of this method to measure the matrix component of drainage may be useful in quantifying the by-pass component of the total drainage, the by-pass plus matrix that is measured by the tension lysimeter.

2.4 Barrel Lysimeter

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.

The barrel lysimeter method (in collaboration with D McGarry, Queensland Department of Environment and Resource Management) was found to overestimate by 47% compared with the equilibrium tension lysimeter. This overestimation can be attributed to three factors. Firstly, the barrel lysimeter measurement area was only 4.4% that of the tension lysimeter and as such is too small to representatively measure drainage at the spatial scale of the furrow-hill intervals or the cracking clay soil structure. Secondly, the backfilled annulus of the barrel lysimeters from ground surface to measurement depth is a high permeability pathway for by-pass flow that was not present prior to installation. Thirdly, the barrel lysimeters apply a constant suction at measurement depth which is often greater than or less than surrounding soil tensions at that depth. This leads to over-estimation of drainage during wet soil conditions and under-estimation when dry.

3.0 GROUNDWATER RECHARGE

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."

Groundwater responses in the unconfined and confined aquifers were previously measured in piezometers installed at the lysimeter facility. Over the three year report period (2008-11) 497 mm of vadose drainage entered the water table, at an average rate 166 mm/year.

During this same period there was a continuous downward gradient between the salty unconfined aquifer and the lower confined aquifer which is used extensively for drinking and irrigation. A total of 677 mm of phreatic leakage occurred through the aquitard into the confined aquifer at an average rate of 226 mm/year.

There was only minor correspondence observed between seasonal deep drainage measured in the lysimeter and recharge at the water table. This is due to factors such as the vastly different measurement scales of the lysimeter and the unconfined aquifer, the attenuation of drainage fronts through the thick clay vadose zone and the relatively short record of drainage and groundwater responses.

There was a notable groundwater response following heavy rain during the 2010-11 summer. A total of 384 mm of rainfall was recorded during the months of November and December 2010. The peak 50 day rainfall rate of 9.8 mm/day was on 4 December 2010. The corresponding peak vadose recharge rate of the water table was 3.6 mm/day on 1 March 2011. Analysis of the event data showed an overall correlation of 0.497 and a time lag of 87 days.

4.0 SOLUTE LEACHING

In addition, the lysimeter facility has provided an opportunity to examine whether drainage from cotton is contaminated by salts and nitrogen fertilizers. 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 has provided insights into fundamental soil processes associated with irrigated agriculture including carbon/nitrogen cycling and changes in soil exchangeable cations chemistry.

During the 2008-09 cotton season 10% of the fertilizer nitrogen applied to the crop was lost in deep drainage. Of the total nitrogen (TN) lost, 59% was as nitrate (NO3-N) and 41 % was as dissolved organic nitrogen (DON-N) compounds. Most of the nitrogen loss occurred during the first four irrigations.

Drainage electrical conductivity (EC) ranged from 1.5 to 13.3 dS/m. The higher EC values result from the relatively greater leaching efficiency during matrix flow. Lower EC values occur from by-pass flow but are still significantly greater than the typical 0.4 dS/m irrigation water quality.

Objectives

2. **List the project objectives and the extent to which these have been achieved, with reference to the Milestones and Performance indicators.**

2.1 OBJECTIVE 1: MEASUREMENT OF THE WATER BALANCE

- **Milestone 1.1 Drainage and water balance of 2012-13 cotton crop measured**

Milestone 1.1 was achieved.

The drainage and water balance dataset for 2012-13 cotton crop was collected, interpreted and reported

The lysimeter and associated equipment was fully operational throughout the 2012-13 cotton season. Cumulative drainage collected in 6 replicate trays at 2.1 m depth was measured at 15 minute intervals. Soil matric potential were measured was measured with tensiometers in two replicated profiles at 1.8 m and 2.1 m depths at 15 minute intervals. Soil water content was measured one day before and two days after each irrigation, and weekly between irrigations, using a neutron moisture meter; measurements were made at seven depths from 0 to 2.1 m in each of four replicate access tubes.

- **Milestone 1.2 Drainage and water balance of 2013 wheat crop and subsequent fallow measured**

Milestone 1.2 was not fully achieved.

The drainage and water balance dataset for 2013-14, under an altered crop rotation, was collected, interpreted and reported, but soil compaction in the field resulted in inaccurate lysimeter control and invalid drainage and matric potential measurements.

In 2014 very little valid drainage data was collected in 2014 due to due to several consecutive hardware failures.

The crop rotation was changed by NSW DPI in the experiment plot where the lysimeter is located. Wheat was not planted and the field was fallow over the 2013 winter. This was followed by a corn crop in the 2013-14 summer and fallow in the 2014 winter.

- **Milestone 1.3 Drainage and water balance of 2014-15 cotton crop and during 2015-16 measured.**

Milestone 1.3 was not achieved.

The drainage and water balance data was collected, interpreted and reported, but analysis of showed very little of the data was valid.

The lysimeter was not fully operational due to numerous consecutive hardware failures.

The 2014-15 cotton crop was followed by wheat in 2015 winter then corn in 2015-16 summer.

- **Milestone 1.4 Improved understanding of drainage drivers and processes**

Milestone 1.4 was achieved.

Detailed analysis of lysimeter drainage from 2006 to 2011 was completed and a scientific paper submitted: Ringrose-Voase, Anthony; Nadelko, Tony (2013). Deep drainage in a Grey Vertosol under furrow-irrigated cotton. Crop & Pasture Science 64:1155–1170.

2.2 OBJECTIVE 2: QUANTIFICATION OF THE CONNECTION BETWEEN DEEP DRAINAGE AND RECHARGE OF THE UNCONFINED AQUIFER.

- **Milestone 2.1 Groundwater behaviour monitored during 2012/13 cotton crop and analysed with respect to drainage data from lysimeter**

Milestone 2.1 was partially achieved.

Groundwater behaviour was monitored during 2012-13 and analysed with respect to lysimeter drainage data. A scientific paper was not submitted.

The plot scale lysimeter drainage and irrigation measurements did not correlate to larger scale groundwater responses. A strong correlation was found between heavy rainfall events and groundwater response, with a weaker correlation to the overall rainfall dataset. The extent of the water table aquifer, and therefore the surface landforms contributing to its responses are also unknown.

Groundwater levels in the unconfined and confined aquifers and barometric pressure were logged hourly during the 2012-13 season. The groundwater data was processed to generate a time series of water table vadose recharge rates, phreatic leakage rates and barometric efficiency. The vadose recharge rates were compared to drainage, rainfall and irrigation infiltration rates for response correlations.

- **Milestone 2.2 Groundwater behaviour monitored during 2013 wheat crop and fallow and analysed with respect to drainage**

Milestone 2.2 was partially achieved.

Groundwater behaviour was monitored, analysed and reported as before. Whilst groundwater responses were compared with rainfall and irrigation infiltration, no valid drainage data were available for comparison. Due to the change of crop rotation in the plot (see milestone 1.2 above), the groundwater behaviour was measured under a differed series of crops.

- **Milestone 2.3 Groundwater behaviour monitored during 2014/15 cotton crop and during 2015/16 and analysed with respect to drainage data from lysimeter**

Milestone 2.3 was partially achieved.

Groundwater behaviour was monitored, analysed and reported as before, but no valid drainage data were available for comparison. Groundwater responses were compared with rainfall and irrigation infiltration under a different crop rotation.

As before, the plot scale irrigation measurements did not correlate to larger scale groundwater responses, but there was a strong correlation with heavy rainfall events and a weaker correlation to the overall rainfall dataset.

2.3 OBJECTIVE 3: INVESTIGATION OF GEOCHEMICAL CYCLING AND LEACHING OF SALTS, NITROGEN AND CARBON.

- **Milestone 3.1 Design and install EC measurement and water sampling equipment. Design sampling protocol**

Milestone 3.1 outcomes were achieved by an alternate method.

A bromide tracer experiment and sampling program was designed to achieve the same indication of by-pass and matrix drainage flow as the EC measurements, through the differing bromide concentrations and mass fluxes during high frequency sampling.

Potassium bromide was injected into the soil above the lysimeter as concentrations above the natural baseline. A sampling protocol was developed to collect drainage water at the most frequent volume-based intervals that would generate the required sample volumes for all proposed analyses.

- **Milestone 3.2 Drainage collected at frequent intervals throughout 2012/13 cotton season and analysed**

Milestone 3.2 was achieved

Drainage was collected and analysed at frequent intervals during the 2012-13 season and reported.

Drainage from the first irrigation was sampled over a single interval. The bromide tracer was injected above the lysimeter immediately prior to the second irrigation. Drainage was sampled during the second irrigation at nine intervals over the first two days and once again just prior to the next irrigation. The third irrigation was sampled over five intervals and once more just prior to the next irrigation. The forth irrigation was sampled over a single interval. There was insufficient drainage volume for analysis from the fourth irrigation, so drainage was not sampled but was left to accumulate and sampled after the fifth irrigation. All samples were analysed for a suite of anions, cations, nitrogen compounds, carbon compounds, pH and EC.

- **Milestone 3.3 Drainage collected and analysed during 2013 wheat crop and subsequent fallow**

Milestone 3.3 was not achieved.

Drainage samples were collected at the end of each phase of the crop rotation. Sample volumes were insufficient for analysis due to field compaction causing inaccurate lysimeter control and under-collection of drainage.

The sequence of crops was different to that planned due to a change in the crop rotation in the plot (see milestone 1.2)

- **Milestone 3.4 Drainage collected at frequent intervals throughout 2014-15 cotton season and 2015-16 and analysed**

Milestone 4.3 was partially achieved

Drainage samples were collected at the end of each phase of the crop rotations during this period and analysed for pH, EC and nitrogen compounds. Drainage rate data were not available due to inaccurate lysimeter control from hardware failures, which prevented calculation of solute mass fluxes.

A scientific paper was submitted: Macdonald BCT, Ringrose-Voase AJ, Nadelko AJ, Farrell M, Tuomi S, Nachimuthu G. (2016) Dissolved organic nitrogen contributes significantly to leaching from furrow irrigated cotton-wheat-maize rotations. Soil Research.

The 2014-15 cotton crop was followed by wheat in 2015 winter then corn in 2015-16 summer.

2.4 OJECTIVE 4: IMPROVE THE APSIM CROP MODEL.

- **Milestone 4.1 Conceptual water balance model for cracking clays formalised for use in APSIM.**

Milestone 4.1 was achieved.

A conceptual model for soil water dynamics was developed from measurements on deep drainage, soil water suction and calculated gradients that distinguishes the two flow situations, by-pass and matrix flow.

All available data for input, such as rainfall, irrigation, temperature, solar radiation, crop management and fertilisation were used as input into the ASPSIM-Soilwat model to identify the differences between simulated soil water content and drainage and those measured at the lysimeter site. Further work evaluated the crop timing and yield between the APSIM-Cotton and standalone OZCOT models. The need to incorporate the functionality of APSIM *kl* and *xf* factors into APSIM-cotton was identified. Development of the availability of *kl* values in APSIM-Cotton has now been completed, but field verification is still required. The development of *xf* values for APSIM-Cotton is currently in progress.

Methods

3. **Detail the methodology and justify the methodology used. Include any discoveries in methods that may benefit other related research.**

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). 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 (Figs 1 and 2). 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 x 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 (Fig. 1). The trays were installed at 2.1 m depth by tunnelling horizontally through a window cut in the wall of the access shaft. 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.

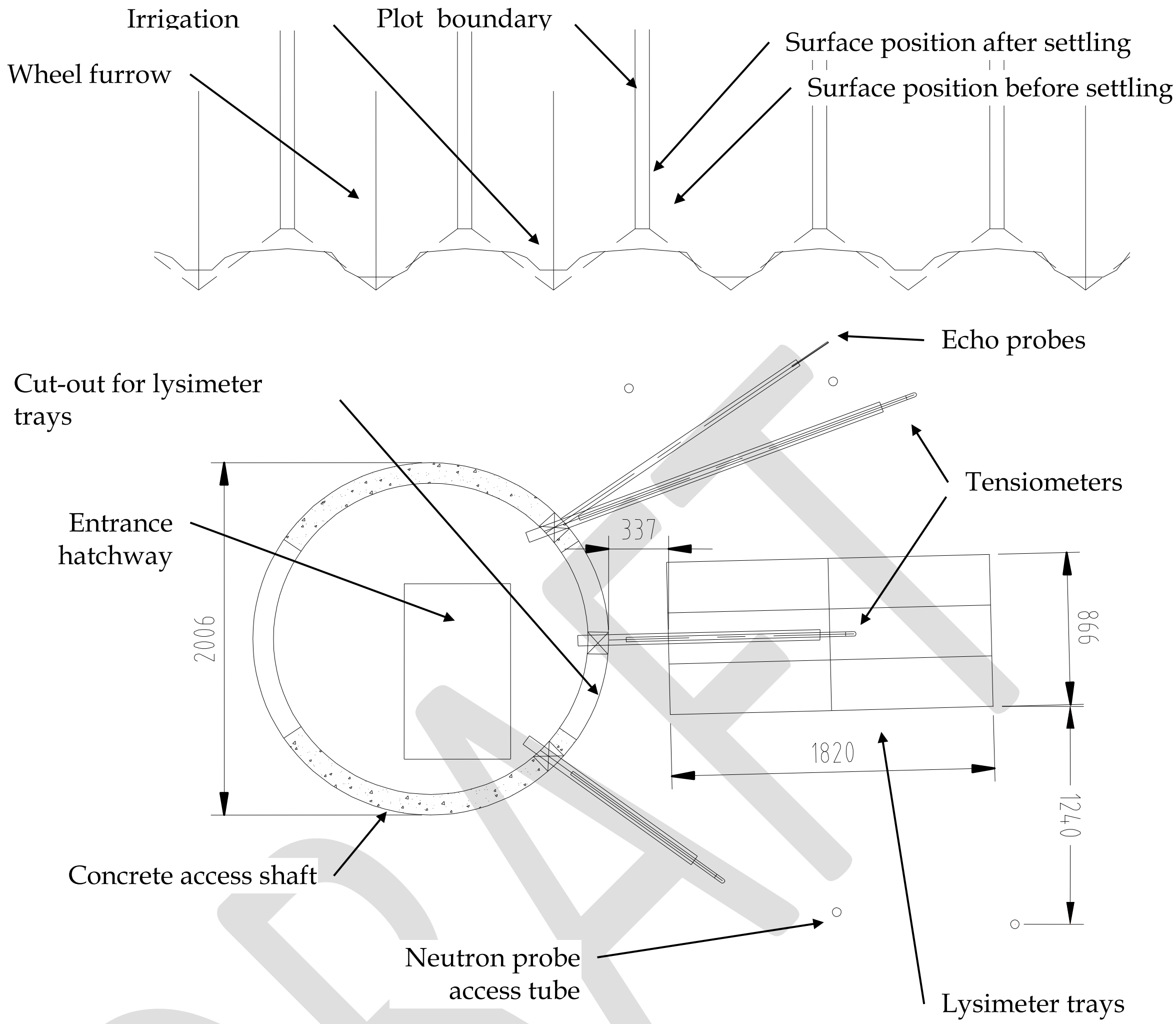

Figure 1. Plan view of lysimeter trays, access shaft, and other instruments. Dimensions in millimetres.

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 <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.

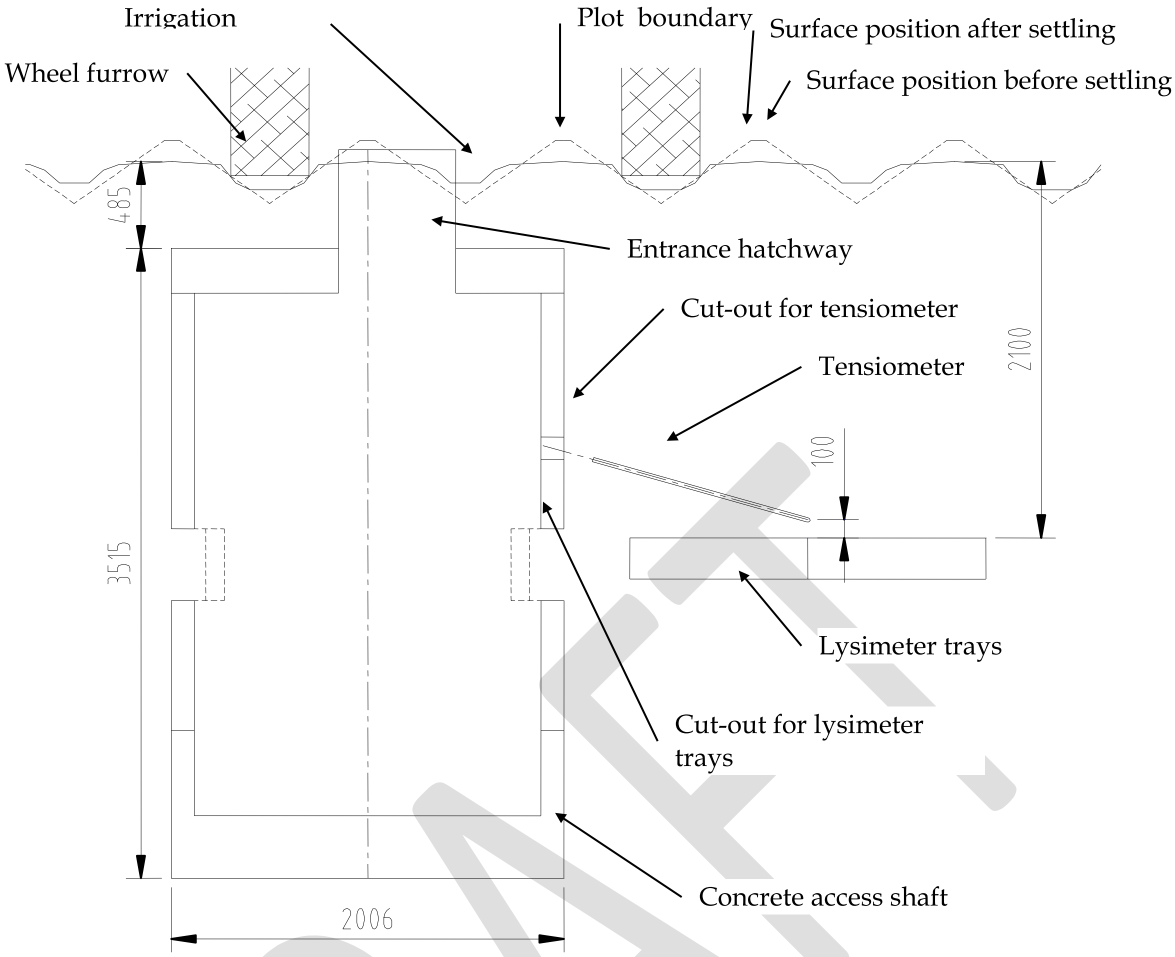

Figure 2. Vertical cross-section through the centre of the access shaft at 90° to the furrows. Dimensions in millimetres.

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 um 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 (Fig. 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.

3.2.3 Irrigation Infiltration

Irrigation is difficult to measure when applied by furrow without metering volumes of water applied at the head ditch and runoff at the tail drain. In this case the irrigation infiltration was estimated as the change in soil water storage between consecutive soil water content measurements, generally the day before and two days after each irrigation. The infiltration was reported as water volume in the soil from 0 – 2.1 m depth, above the depth of lysimeter drainage measurement.

3.2.4 Soil Water Status

Soil water content was measured by neutron moisture meter at intervals throughout the season. For simplicity the soil water content (SWC) is expressed as the soil water deficit (DUL – SWC, where DUL is the drained upper limit and SWC is soil water content) 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).

3.2.5 Soil water potential

Tensiometers were used to measure matric potential throughout the profile at 15 minute intervals. However, 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 measured 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 well, refilling the tensiometers can create short-term offsets in measured potentials due to effects on the soil surrounding tensiometer cup.

It is the differences between the matric potentials of different layers, combined with gravity, that create the hydraulic gradient. 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 hydraulic gradients were calculated between the matric potentials measured at 1.8 and 2.1 m depths. 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:

Gradient is the matric potential gradient in kPa/m

Ψ is the matric potential in kPa at 1.8 or 2.1 m depth

Z is the measurement depth in metres

g is the gravitational constant 9.81 m/s^2

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.

3.2.6 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 a TPS WP81 (TPS Brendale, Qld) and a k=10 GK Series Conductivity Sensor. 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. All of the dissolved nitrogen species in the drainage water were analysed with an Alpkem Segmented Flow Analyser, Alpkem Corporation, Perstorp Analytical Company, Wilsonville, OR 97070 USA. Nitrate/Nitrite-N (NOx-N) and Ammonium-N were analysed simultaneously on a separate channels with the cadmium reduction method (Method 4500-Nitrate E; Rice et al. 2012) and with the alkaline phenol method (Method 4500-Ammonia F; Rice et al. 2012). Total nitrogen (TN) was analysed on duplicate sample which was first digested using the persulfate oxidation method (Method 4500-Nitrogen C; Rice et al. 2012) and NOx-N concentration was subsequently determined by the cadmium reduction method (Method 4500-Nitrate E; Rice et al. 2012)

3.3 Groundwater

3.3.1 Piezometers

Two piezometers, P1 and P2, are located 5 m and 10 m east of 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 21 m below ground surface (bgs), near the base of the unconfined water table aquifer, and P2 is screened at 35 m bgs near the top of the confined aquifer.

The groundwater head in each piezometer is recorded hourly by submersible, temperature-corrected, un-vented level loggers suspended beneath the water surface. 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. A barometric pressure sensor in the lysimeter manhole is also logged hourly by the lysimeter data logger.

The piezometer screen and level logger elevations are surveyed to a local benchmark relative to the topographic ground surface elevation of 200.0 m. Gauge levels are calculated by subtracting barometric pressure from absolute levels, plus the sensor-specific zero point and altitude offsets. Hydraulic heads are calculated as the gauge sensor levels plus the sensor elevations. Standing water levels (SWL) are the depth of the water surface below ground surface.

3.3.2 Unconfined aquifer recharge and discharge

Water leaching out of the root zone flows as deep drainage through the vadose zone, ultimately reaching the unconfined aquifer and recharging the groundwater. The vadose flow rate is dependent on the unsaturated hydraulic conductivity and soil hydraulic gradients, both of which vary non-linearly in relation to the water content and particle size distribution. Variations in vadose soil texture with depth and changes in soil water content over time result in considerable variation in rates of unsaturated flow through the vadose zone.

The phreatic leakage is saturated flow through the aquitard between the unconfined and confined aquifers. Its flow rate is directly proportional to the vertical hydraulic gradient between the aquifers and the hydraulic conductivity of the aquitard. While the aquitard hydraulic conductivity is effectively constant the magnitude of the hydraulic gradient can vary greatly along with its direction. Leakage can be downward as discharge into the confined aquifer, upward as recharge from the confined aquifer, or zero.

Thus changes in the head of the unconfined aquifer (h_1) are due to both recharge from the vadose zone and leakage between the aquifers. As a result they cannot be used to directly indicate the magnitude of recharge. In order to estimate when recharge was occurring and its magnitude, the following method was developed.

The vertical hydraulic gradient between piezometers is calculated by the following equation:

$$\nabla h = \frac{(h_2 - h_1)}{(z_2 - z_1)}$$

Where:

∇h is hydraulic gradient (negative downward)

h_1 is piezometer P1 hydraulic head in metres

h_2 is piezometer P2 hydraulic head in metres

z_1 is piezometer P1 screen elevation in metres

z_2 is piezometer P2 screen elevation in metres

The unconfined aquifer rates of change are calculated as the change in hydraulic head over a 2 hour centred time window.

Changes in the hydraulic gradient over time are dominated by the changes in the hydraulic head of the confined aquifer which show much greater variation than that of the unconfined aquifer. Comparing the hydraulic gradient to the rate of change of the unconfined heads clearly indicated gradient-driven head changes, buffered by the clay aquitard.

The hydraulic gradient and the rates of change of the unconfined aquifer head were smoothed with a least square filter with a 50 day window, low-passing at a frequency of 0.02 cycles per day (cpd). This filter was found to provide the greatest correlation between the hydraulic gradients and rates of change of the unconfined aquifer head.

The observed rate of change of the unconfined aquifer head, $(\partial h_1/\partial t)_{observed}$, is the sum of two components, the vadose recharge rate and phreatic leakage rate:

$$(\partial h_1/\partial t)_{observed} = (\partial h_1/\partial t)_{recharge} + (\partial h_1/\partial t)_{leakage}$$

There is nearly always a hydraulic gradient between aquifers and therefore phreatic leakage is occurring. Deep drainage though, generated by inputs of rainfall and irrigation at ground surface, is often near zero. When the vadose recharge rate approaches zero, the phreatic leakage rate component approaches parity with the observed head rate of change. At this point the ratio of phreatic leakage rate to the hydraulic gradient is maximized. This provides the possibility of estimating the relationship of the head rates of change due to leakage and the hydraulic gradients between the aquifers at other times.

The eight year piezometer dataset of the ratio of the rate of change of the unconfined aquifer head, $(\partial h_1/\partial t)_{observed}$, to the hydraulic gradient, ∇h, was examined for the time of the local maximum when $(\partial h_1/\partial t)_{observed}$ was negative (i.e h_1 was deceasing) and ∇h was negative (downward). The ratio was 11.29016 when these conditions were met on 11 May 2016 02:00 h. This value was used to estimate the phreatic leakage rates at other times using the equation:

$$(\partial h_1/\partial t)_{leakage} = 11.29016\,\nabla h$$

From the phreatic leakage rates, the vadose recharge rates at those times were estimated as the difference of observed head rate of change minus the phreatic leakage rate. Further, Volumetric vadose recharge and phreatic leakage rates (i.e. in mm) can be estimated by multiplying the head rates of change by a factor of 0.23, a typical specific yield value for granular soils in the aquifer.

3.3.3 Unconfined aquifer barometric efficiency

Barometric efficiency (BE) is the ratio of the change in aquifer water-level to the change in atmospheric pressure, calculated by the equation:

$$BE = \frac{\Delta h\,(\rho g)}{\Delta Pa}$$

Where:

BE is barometric efficiency

Δh is the change in piezometric water level

ΔPa is the change in atmospheric pressure

ρ is the fluid density

g is the gravitational constant (9.81 m/s^2)

Water level fluctuations in a piezometer tapping a deep unconfined aquifer are caused by differences in barometric pressure at the water table to that at the water surface in the piezometer. Barometric pressure changes transmitted to the water table through the vadose zone are attenuated and delayed by the pneumatic diffusivity of the soil, while the barometric pressure is fully and instantly transmitted to the water surface in the piezometer. The pneumatic diffusivity of the soil is directly proportional to its air-filled porosity, and so inversely proportional to its water-filled porosity. The effect of atmospheric pressure in the piezometer on the pressure in an expansive aquifer is negligible.

The barometric efficiency has been calculated by graphical or numerical analysis of long-term sets of water level and atmospheric pressure measurements as well as from the periodic S2 semi-diurnal components of these measurements. These methods aim to derive a single long-term BE value representative of the aquifer, minimising or ignoring short-term fluctuation effects. But short-term BE variations are of much value, providing insights into changes in aquifer confinement by vadose zone sealing through soil water storage changes.

Spectral analysis of the hydraulic heads and simulated gravity at the lysimeter location indicated no significant periodic gravity components unique to earth tides present in the hydraulic head spectra. The barometric pressures were first converted to water column equivalents. The semi-diurnal components of the hourly barometric and P1 hydraulic heads were extracted by band-pass least-square filtering between frequencies of 1.995 and 2.005 cpd with a 12 hour window. The amplitude of each successive sinusoidal cycle was calculated from each and from these the BE was calculated at 12 hour intervals.

The semi-diurnal BE values exhibit considerable fluctuations, with abrupt increases coinciding with rainfall and irrigation events. The BE values on these dates was not removed from the data set, but rather the calculated BE data was smoothed with low pass filters using 16 day and 50 day windows.

3.4 Weather

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

3.5 Operations

The cropping and operational state during this report period are shown in Table 1. The original cotton-wheat-fallow crop rotation in the field that lysimeter is located in was changed by NSW DPI shortly after the start of the project. Data was collected during two cotton crops, two wheat crops, three corn crops and three fallow periods.

Field management operations were conducted during the winters of 2012, 2013 and 2015. In July 2012 the field C1 was ripped to 30 cm depth then laser levelled. The ground over the lysimeter received some machine traffic but ripping was minimal due to the proximity of the manhole hatch and neutron moisture tubes.

In May 2013 the field C1 was ripped to 30 cm depth, again with some machine traffic over the lysimeter but minimal ripping activity. The field's plots were GPS aligned and adjusted to 8-row increments but the alignment above the lysimeter remained unchanged. The field was then left fallow until the 2013-14 corn crop.

In August 2015 the lysimeter plot was ripped to 50 cm depth along the furrows, 10 m upstream and downstream of the lysimeter, over the first 12 rows in an attempt to remediate the soil compaction at the lysimeter.

Table 1: Cropping and operational status at the ACRI lysimeter facility.

Dates	Crop (former)	Operational State
Jun 2011 - Aug 2011	Wheat	Operational
Sep 2011 - Mar 2012	Corn (wheat-fallow)	Operational
Apr 2012 - Sep 2012	Fallow	Operational
Oct 2012 - May 2013	Cotton	Operational
Jun 2013 - Nov 2013	Fallow (wheat)	Operational
Dec 2013 - Apr 2014	Corn (fallow)	Non-operational (soil compaction)
May 2014 - Sep 2014	Fallow	Non-operational (74 days of instrument failures)
Oct 2014 - Apr 2015	Cotton	Non-operational (220 days of instrument failures)
May 2015 - Nov 2015	Wheat	Non-operational (186 days of instrument failures)
Dec 2016 – April 2016	Corn (cotton)	Non-operational (160 days of instrument failures)

Results

4. Detail and discuss the results for each objective including the statistical analysis of results.

4.1 OBJECTIVE 1: MEASUREMENT OF THE WATER BALANCE.

Drainage and water balance were measured under one corn crop, one cotton, one winter wheat crop and two fallow periods. Table 2 and 3 summarize the drainage measured by the lysimeter and its EC, together with inputs of rainfall and irrigation for 2011-12 and 2012-13, respectively.

The 2011-12 measurements are from lysimeter operation between non-consecutive CRDC projects. Drainage values were invalid following the 2013 fallow and are not presented.

Table 2. Drainage and electrical conductivity of the leachate during the 2011 fallow period, 2011 wheat crop, 2011-12 corn crop and 2012 fallow period. (Amounts shown are from the date of the event until the date of the next event shown in the next row). "↓" indicates drainage was accumulated over several events.

Crop	Event	Date	Rainfall	Irrigation infiltration*	Tension lysimeter	
					Drainage, mm	**EC, dS/m**
			mm	**mm**		
Fallow	Cotton Pick	2-Apr-11	88.3		0.1	8.5
Wheat	Sown	25-Jun-11	0.3		0.0	↓
	Irrigation 1	7-Jul-11	12.4	123.3	0.2	↓
	Sprayed Out	16-Aug-11	74.8		0.6	↓
Corn	Sown	19-Sep-11	0.5		0.1	↓
	Irrigation 1	28 Sep-11	122.6	39.5	0.2	6.6
	Irrigation 2	11-Nov-11	398.5	77.6	2.4	↓
	Irrigation 3	10-Jan-12	325.2	62.9	0.9	↓
Fallow	Corn Harvest	14-Mar-12	22.7		0.5	↓
		30-Apr-12	184.3		0.6	9.7
	Cotton Sown	27-Oct-12				
Totals			**1229.6**	**303.3**	**5.7**	
Rainfall + irrigation				**1532.9**		

The 2011 wheat crop generated 0.8 mm of drainage, with one irrigation applied shortly after sowing. Soil water deficits gradually increased and matric potentials decreased during this period and there was no correlation between drainage and either irrigation or rainfall. This crop was sprayed out early and did not reach maturity. This was because the rotation experiment in the lysimeter field was changed by NSW DPI to include corn as a third crop in the two year rotation.

During the 2011-12 corn season 3.6 mm of drainage was recorded. There were only three irrigations during the 2011-12 corn crop, less than typically would be required. This was due to high rainfalls with 846.8 mm being recorded, the bulk of which occurred after the second irrigation. Most of the drainage, 2.4 mm, occurred from the second irrigation, but this included a long interval with much rainfall before the third irrigation (Fig. 3).

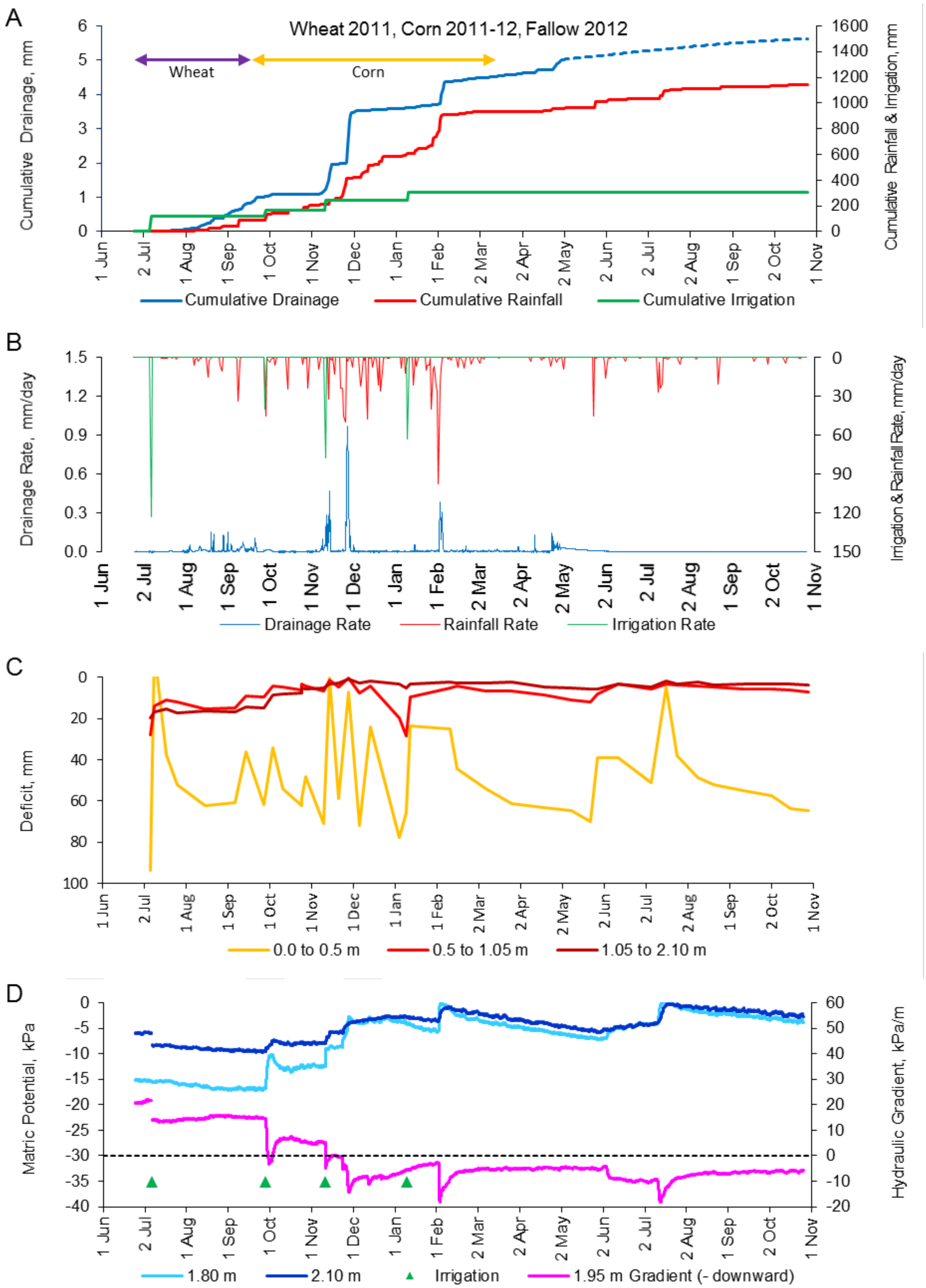

Figure 3. A) Cumulative drainage (left axis) and cumulative rainfall and irrigation (right axis) during the 2011 wheat and 2011-12 corn crops and the subsequent fallow. B) Drainage rate (left axis) and rainfall and irrigation rate (right axis). C) Soil water deficit of three layers (4 replicates). D) Matric potential (left axis) measured by tensiometers (2 replicates) and hydraulic gradient between tensiometers (right axis).

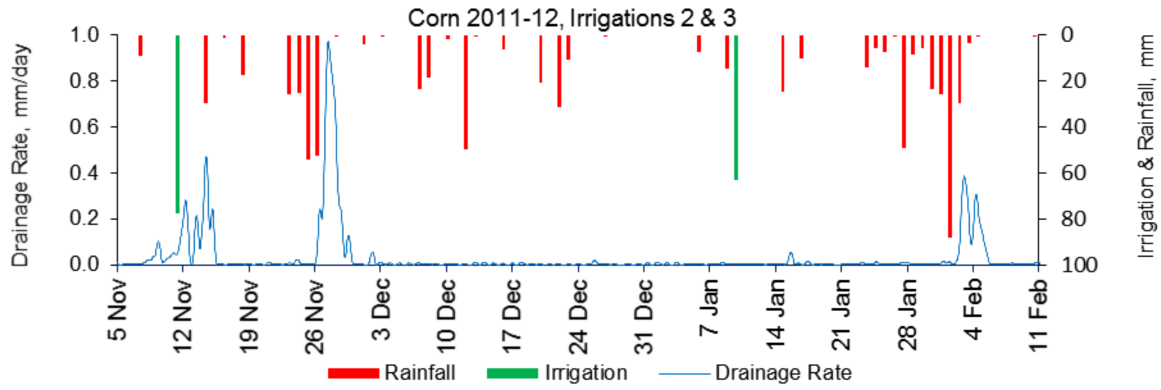

Figure 4. Detailed drainage rates (left axis) and rainfall and irrigation (right axis) following the second and third irrigations of the 2011-12 corn crop.

There was no correlation between the first irrigation and drainage. There was a response in the subsoil though, with increased soil matric potentials, decreased soil water deficits and decreased matric hydraulic gradient.

There was good correlation between drainage and the second irrigation (Figs 3B and 4), drainage reached 2.1 m depth 7 hours after the irrigation advanced over the lysimeter. The third irrigation refilled the soil water deficit that had developed at 0.1 - 1.05 m depth with no significant drainage response. There was a final well correlated drainage response from the large February rainfall, by which time the crop had reached maturity.

There were 6 irrigations during the 2012-13 cotton season with 13.1 mm of total drainage measured (Table 3, Fig. 5). Very little rain fell in the early season, requiring irrigation 2, the first in-crop irrigation, to be just 38 days after planting and the third irrigation 14 days after that.

Drainage responses correlated well to the first three cotton irrigations (Figs 5B and 6) with all three exhibiting the same irrigation response time lag. Drainage reached 2.1 m depth 2 hours after irrigation water advanced over the lysimeter. The first three irrigations also generated most of the season’s drainage, coinciding with downward matric gradients and small subsoil deficits.

Matric potentials responded to all irrigations, though there was no significant drainage response from the last three irrigations. The drainage recorded from the final irrigation was due mainly to the rainfall shortly after the irrigation.

Table 3. Drainage and electrical conductivity of the leachate during the 2012-13 cotton crop and 2013 fallow as measured by variable tension lysimeter. (Amounts shown are from the date of the event until the date of the next event shown in the next row). "↓" indicates drainage was accumulated over several events.

	Event	Date	Rainfall	Irrigation infiltration*	Tension lysimeter	
			mm	mm	Drainage, mm	EC, dS/m
Cotton	Sowing	27-Oct-12	0.3		0.4	4.1
	Irrigation 1	30-Oct-12	21.9	50.5	2.8	4.5
	Irrigation 2	4-Dec-12	4.9	45.3	3.9	3.1
	Irrigation 3	18-Dec-12	45.9	27.4	2.9	2.5
	Irrigation 4	10-Jan-13	22.2	53.6	0.1	1.8
	Irrigation 5	24-Jan-13	109.7	56.8	0.2	1.4
	Irrigation 6	21-Feb-13	122.9	80.7	2.8	↓
Fallow	Cotton Pick	10-May-13	132.7		15.6	5.5
		15-Nov-13	60.7		1.3	2.6
	Corn Sown	13-Dec-13				
Totals			**521.2**	**314.3**	**29.9**	
Rainfall + irrigation			**835.5**			

Drainage continued to be measured over the 2012 fallow despite significant, post-cotton decreases in matric potentials and upward matric hydraulic gradient. There was almost 200 mm of rainfall distributed throughout the fallow, which may have drained as by-pass flow though macropore connections established within the relatively, dry post-cotton soils.

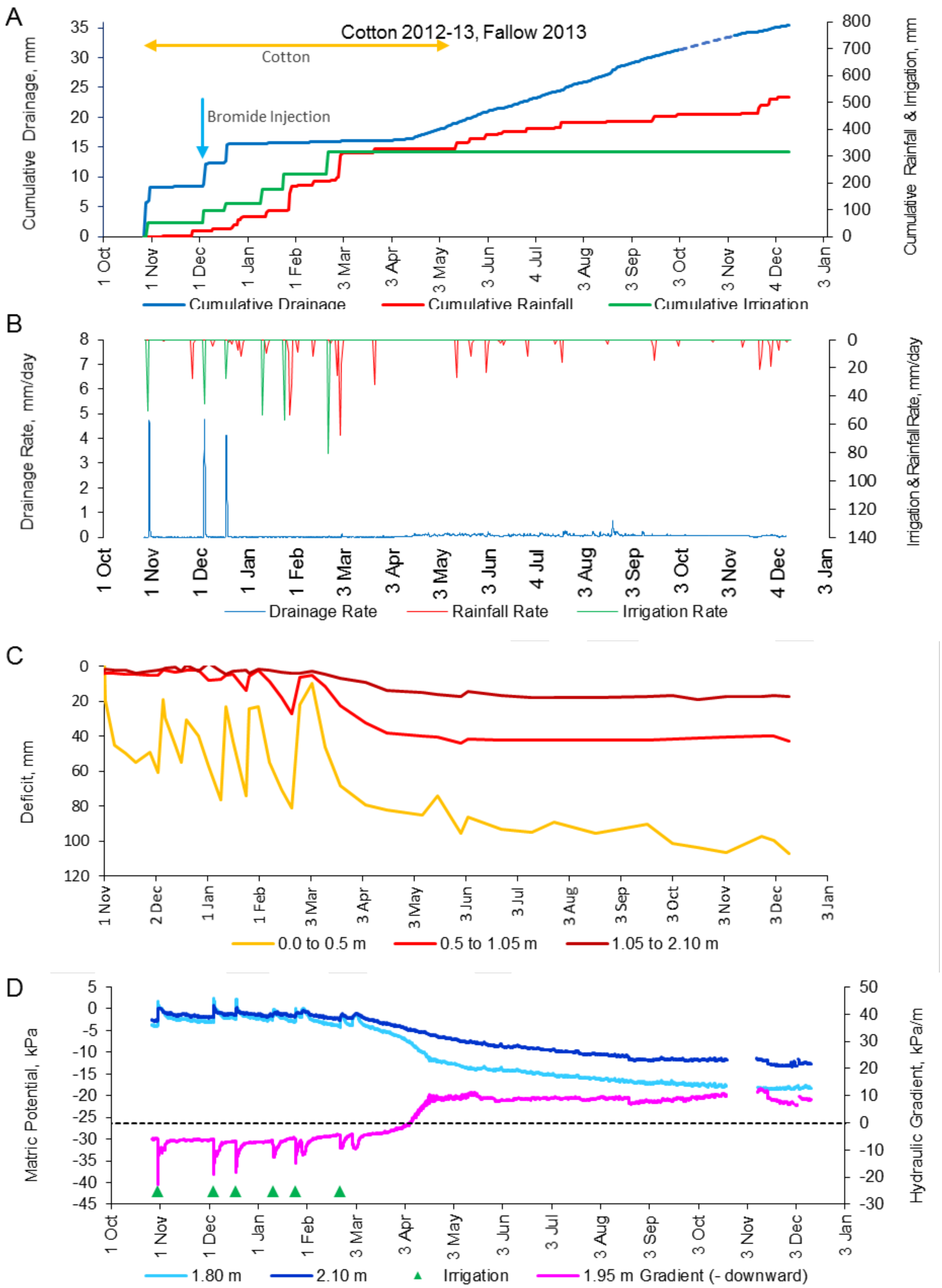

Figure 5. A) Cumulative drainage (left axis) and cumulative rainfall and irrigation (right axis) of the 2012-13 cotton crop and subsequent fallow. B) Drainage rate (left axis) and rainfall and irrigation rate (right axis). C) Soil water deficit of three layers (4 replicates). D) Matric potential (left axis) measured by tensiometers (2 replicates) and hydraulic gradient between tensiometers (right axis).

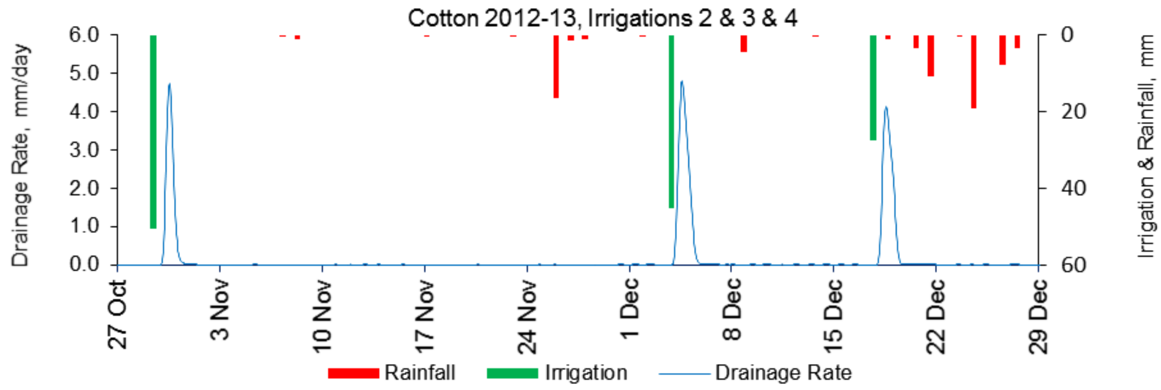

Figure 6. Detailed drainage rates (left axis) and rainfall and irrigation (right axis) after the second third and fourth irrigations of the 2012-13 cotton crop.

The 2013-14 crop rotation was changed by NSW DPI in the experiment plot where the lysimeter is located. Wheat was not planted and the field was fallow over the 2013 winter. This was followed by a corn crop in the 2013-14 summer and fallow in the 2014 winter.

Soil compaction from machine traffic and soil settlement had accumulated over the lysimeter as a result of it not receiving the same mechanical operations as the remainder of the plot. During seasonal cultivations the machine implements are raised above the ground surface as the tractor passes over the lysimeter. Manual field operations over the lysimeter cannot replicate the degree of soil disturbance achieved by mechanical operations.

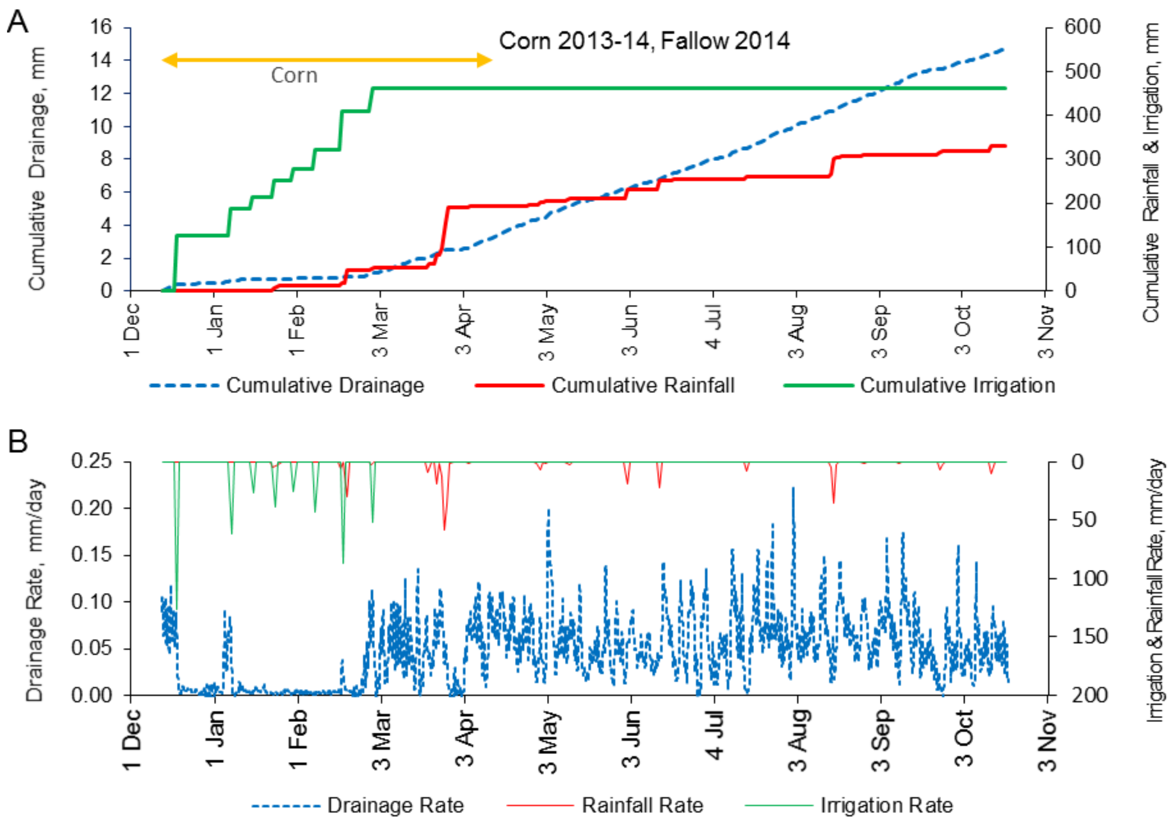

Figure 7. A) Cumulative drainage (left axis) and cumulative rainfall and irrigation (right axis) during the 2013-14 corn crop and subsequent fallow. B) Drainage rate (left axis) and rainfall and irrigation rate (right axis).

In May 2013 the experimental block where the lysimeter is located was ripped prior to realignment of its plots. Compaction from the machine traffic over the lysimeter was again not effectively ameliorated due to limited access for the implement around the hatch and soil sensors. During the 2013-14 corn crop, the soil over the the lysimeter collection trays was more highly compacted than that over the tensiometers which control the vacuum in the lysimeter trays. Greater drainage over the control tensiometers created greater soil moistures and lower tensions there. The vacuum applied to the lysimeter trays, based on the control tensiometer tension, was therefore much less than the soil tension above the trays. This caused constant under-collection of drainage, with further abrupt decreases in collection rates each time a wetting front from irrigation or rainfall reached the control tensiometers (Fig. 7B).

In August 2014 the furrows above the lysimeter and adjacent area were deep ripped to remediate the soil compaction. Following the ripping several consecutive hardware failures occurred resulting in only short intermittent periods of valid fallow drainage data.

The 2014-15 cotton crop was followed by wheat in 2015 winter then corn in 2015-16 summer. Detailed post-analysis of operational and drainage data after the final measurement season revealed very little valid drainage data was collected over 2014-15 and 2015-16 seasons. This was due to numerous consecutive hardware failures, including sacrificial lightning surge protection components, tensiometers, main battery, main solar regulator and tensiometer power supply.

4.2 OBJECTIVE 2: QUANTIFICATION OF THE CONNECTION BETWEEN DEEP DRAINAGE AND RECHARGE OF THE UNCONFINED AQUIFER.

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 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 historically 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.

Bore P1 was drilled on 28 August 2006. The stratigraphy consisted of 4 m of clay overlying 7 m of silt and clay. This was underlain by the unconfined aquifer from 11 to 24 m below ground surface (bgs), comprising 8 m of sand over 5 m of gravel. The borehole was completed at 24 m bgs where the gravel became silty and piezometer P1 screened at 20 to 21 m bgs. The standing level of the water table was 14.50 m bgs on 1 September 2006.

The two piezometers were installed in a separate bores rather than nesting the casings in a single borehole. This was done to avoid possible annular leakage through seals as the 80 mm diameter of the available PVC casings was large relative to the 200 mm bore diameter. Although the bores were only 5 m apart there were stratigraphic differences between them over their replicated depths.

Bore P2 was drilled on 29 August 2006 and intercepted 7 m of clay over 1 m of silt and clay. Below this the unconfined aquifer was intercepted at 8 to 23 m bgs and consisted of interbedded layers of silt, sand and gravel to a depth of 23 m bgs. This was underlain by silt and clay with interbedded sand and gravel layers to a depth of 32 m bgs. Below this the confined aquifer was encountered, consisting of gravel and sand. The borehole was completed in clayey sand at 38 m bgs and the piezometer was screened from 34 to 35 m bgs. The standing water level of the confined aquifer was 17.75 m bgs on 1 September 2006.

Groundwater Responses

P1 hydraulic heads in the unconfined aquifer varied by only 1.8 m during the report period (Fig. 8A). The standing water levels ranged between 14.7 m and 16.5 m bgs with levels exhibiting no overall directional trend. The aquifer remained partially unsaturated; water table levels were 3.8 m to 5.4 m below the top of the 13 m thick sand and gravel stratum.

P2 hydraulic heads in the confined aquifer varied by 7.8 m during this report period (Fig. 8A). The standing water levels ranged between 15.1 m and 22.9 m bgs. The aquifer has remained confined, hydraulic heads were 9.1 m to 16.9 m above the aquitard base.

The large fluctuations in confined aquifer head are caused by pumping from local irrigation bores, three of which are less than 3 km from the piezometers in field C1 at ACRI. These bores are typically cased with screens across all sand and gravel strata between the top of the aquifer and the completion depth at bedrock.

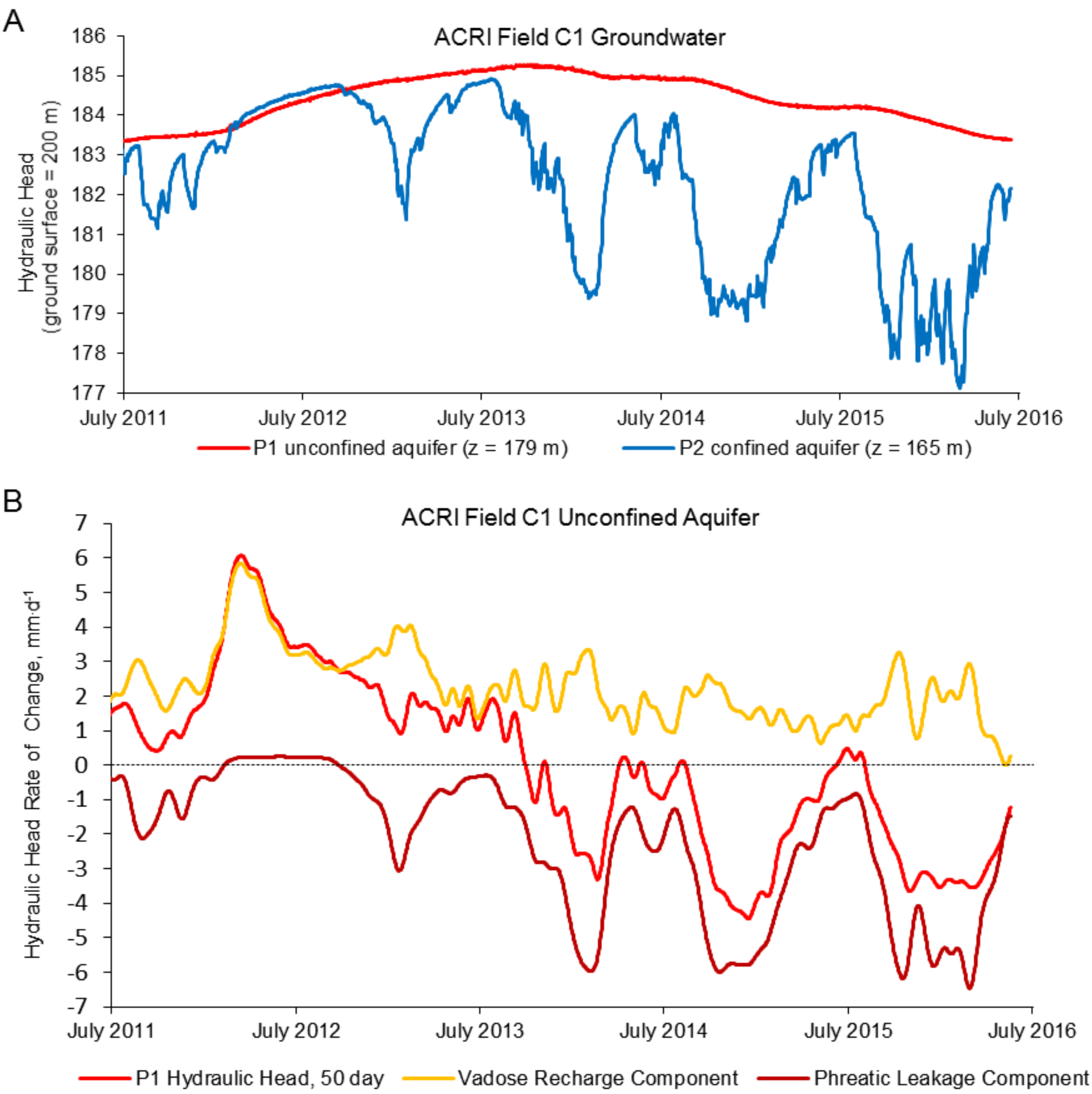

Figure 8. A) Piezometers P1 and P2 hydraulic heads. B) Unconfined aquifer rate of change of hydraulic head and partitioned recharge and discharge components.

The unconfined aquifer does not exhibit rapid responses to the confined aquifer pumping as these head changes are damped out by the clay aquitard. It also does not respond rapidly to rainfall and irrigation induced drainage as these are damped by the thick clay vadose zone. Vertical hydraulic gradients ranged from +0.016 (upward) to -0.423 (downward) during this report period. Gradients were downward during the majority of the report period during which time the water from the unconfined aquifer was continuously leaking through the aquitard into the confined aquifer.

The hydraulic gradient reversed for 226 days beginning on 10 February 2012 following regional flooding. A total of 691 mm of rainfall was recorded over the four months of November 2011 to February 2012. The lysimeter field was inundated under up to 0.5 m of standing water for several days. During this time the unconfined aquifer was receiving recharge from both vadose zone drainage and upward phreatic leakage from the confined aquifer.

Following this flood very little pumping from the confined aquifer occurred as allocations of river water were available for irrigation. This resulted in significant recovery of confined aquifer pressures over the next two years. This was followed by decreasing river water allocations and increasing groundwater pumping with corresponding decreases in confined aquifer pressures and increased hydraulic gradients between aquifers.

The observed water table level in the unconfined aquifer changes very slowly over many seasons. These changes are the net response to two independent components, vadose recharge and phreatic leakage, which are damped by the thick clays of the vadose zone and aquitard. The partitioned vadose recharge and phreatic leakage rates from the unconfined aquifer (Fig. 8B), as change of head, show the independent nature of these components.

Connection Between Deep Drainage And Recharge Of The Unconfined Aquifer

The 50 day vadose recharge rates, as change of head, were converted to volumetric units by applying a// factor of 0.23, a typical specific yield for the granular aquifer soils. The volumetric rate of vadose recharge was integrated to derive the cumulative recharge over the report period. These are shown in Fig. 9C. For response comparison the 50 day rainfall, irrigation and lysimeter drainage rates (Fig. 9A) and unconfined BE (Fig. 9B) are also shown.

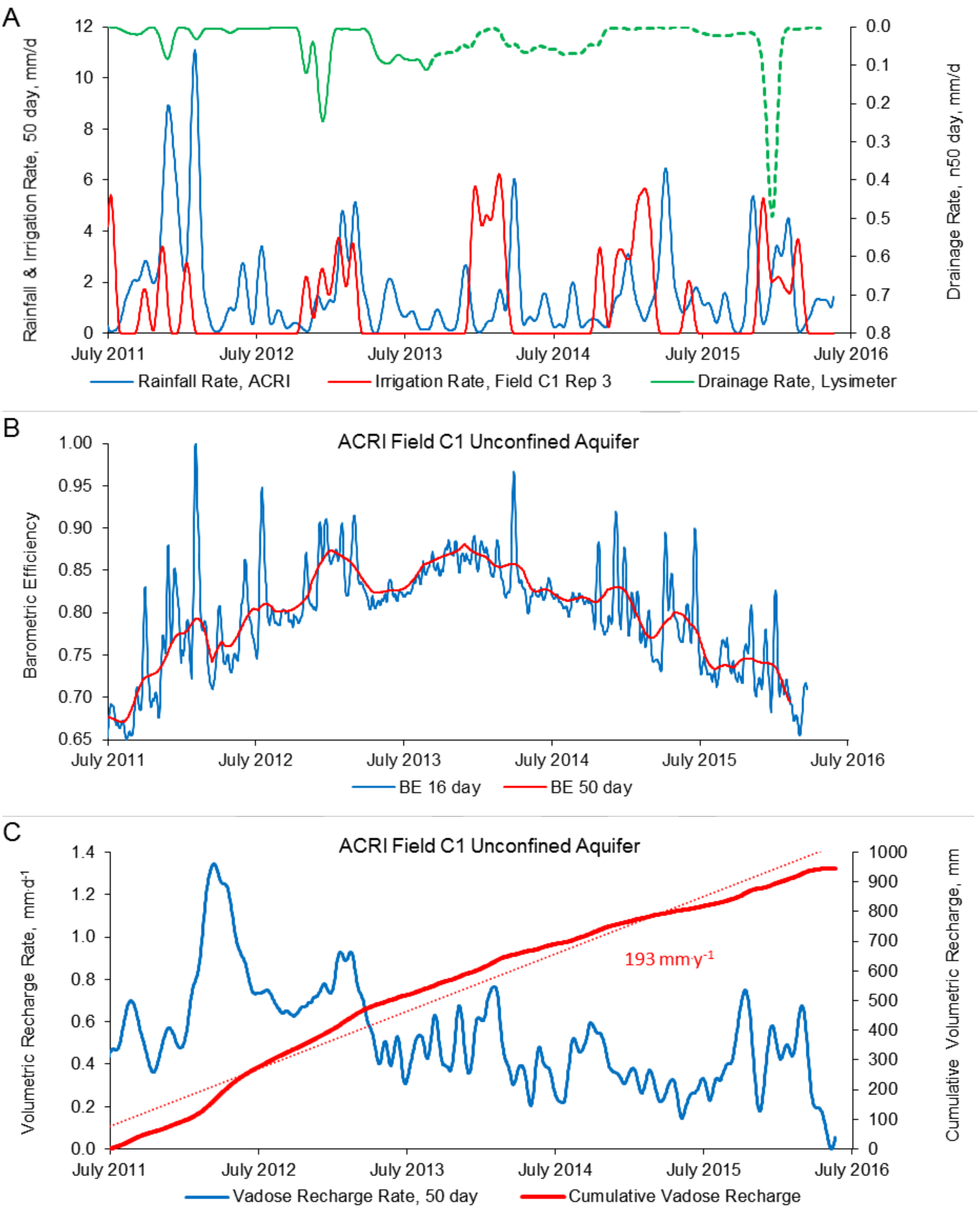

Figure 9. A) Rainfall rate and irrigation rate (left axis), Drainage rate (right axis). B) Barometric efficiency. C) Volumetric vadose recharge, rate (left axis) and cumulative (right axis) based on 0.23 specific yield.

Analysis of the valid lysimeter drainage results to July 2013 showed no correlation with to the unconfined vadose recharge. There was also no correlation between irrigation infiltration and vadose recharge for all data to 2016. There is a correlation (0.357) between rainfall and vadose recharge, with an 802 day time lag, and a weaker correlation (0.215) with a 354 day lag. The different spatial measurement scales, and the correlation of recharge to rainfall but not drainage or irrigations, suggests the aquifer is more aerially extensive area than the lysimeter field.

There was a very strong isolated groundwater response following the regional flood in 2011-12. The 50 day rainfall rates peaked twice, on 27 November (8.9 mm/day) and 31 January (11.1 mm/day). A single large vadose recharge rate response peaked on 14 March 2012 at 1.3 mm/day. Analysis of this 4 month period indicated a 92 day lag between the rainfall and recharge. As expected, correlation was high (0.684) for a single response over a short interval. This is very similar to the 87 day lag in recharge response after 384 mm of rain in November and December 2011.

As the clay vadose zone is very thick there is opportunity for BE to be influenced by varying soil moistures distributed within the profile. The strongest correlation over the eight year rainfall and BE data is 0.352 with a 731 day time lag. There are weaker correlations also: 0.318 with an 1111 day lag and 0.132 with a 410 day lag. There is a strong annual periodicity in the rainfall data, and to a lesser extent in the BE data, with both in phase, explaining the roughly one year multiples of lag. The correlation between BE and recharge rate is not as strong (0.072), but is notable by its 688 day time lag.

BE began to increase 5 months prior to the 2011-12 flood, but the increasing trend continued for two years after the flood. It appears that annual rainfall inputs may accumulate in the vadose zone, still migrating as matrix flow at the time of later annual inputs before ultimately reaching the water table as attenuated recharge rate fluctuations. Further ongoing geophysical investigation would be required to quantify the changes in vadose soil moisture and distribution over time.

Groundwater recharge and leakage

A total of 946 mm of volumetric vadose drainage entered the groundwater in the unconfined aquifer over 1785 days since 1 July 2011 at an average rate 193 mm/year (Fig. 9C).

During this same period a total of 932 mm of water leaked downward under a negative hydraulic gradient between the unconfined and confined aquifers at an average rate of 191 mm/year. As well 11 mm flowed upward through the aquitard during 226 days of reverse hydraulic gradient at a rate of 17 mm/year.

The rates of vadose drainage recharging the water table is much larger than the highest in-field drainage rates measured by the lysimeter. The extent of the unconfined aquifer is unknown but likely extends beyond the lysimeter field, underlying other ground surface landforms such as irrigation ditches, main irrigation and tailwater channels, storage dams and roadways at ACRI and possibly neighbouring farms.

The main tailwater channel for all of Chico Block at ACRI is located immediately north and west of field C1 less than 200 m from the piezometers, containing free water rich in nitrogen and salt compounds for much of the irrigation season. The storages and main irrigation channel are farther from the piezometers with better quality water, but contain free water much of the time. As well there may be higher permeability soils present between these landforms and the aquifer, and the thickness of clay above the aquitard may vary.

The possibility of these landforms contributing to the vadose recharge of the groundwater would provide the opportunity to quantify the rate and quality of that recharge at farm scale, rather than the point scale of the lysimeter or an irrigated field alone.

4.3 OBJECTIVE 3: INVESTIGATION OF GEOCHEMICAL CYCLING AND LEACHING OF SALTS, NITROGEN AND CARBON.

4.3.1 Bromide tracer experiment

The proposed EC measurement equipment was to provide automated high frequency measurements of drainage EC. This was to be used as an indication of the relative proportions of rapid by-pass and slower matrix drainage flows based on the differing EC levels of these two distinct drainage types. A bromide tracer experiment was designed as an alternative method better able to quantify the proportions of by-pass and matrix drainage flow.

Bromide, as potassium bromide solution, was injected into a 9 m^2 area of soil above the lysimeter at a rate of 0.42 mol/m^2, equivalent to 336 kg/ha. This rate was designed to provide a detectable drainage responses at 2.1 m depth at concentrations above naturally baseline levels. The Br tracer was applied one day before the second irrigation of the 2012-13 cotton season. The timing of the application was selected to coincide with the irrigations that have historically generated the greatest portion of drainage volumes.

A volume-based sampling protocol was designed. The accumulation of drainage in the lysimeter collection tanks was monitored in real time by telemetry. Drainage samples were then collected in the field at the most frequent intervals that would generate the required sample volumes for all proposed analyses. Alkalinity analysis of samples needed to be completed immediately, with pH and EC measured at this time. Samples were analysed for bromide and other anions, cations, and nitrogen compounds later.

The first irrigation of the 2012-13 cotton season was on 27 October 2012. The drainage from this irrigation was collected as normal on 26 November. Negligible drainage, 0.015mm, occurred over the next 7 days.

The bromide (Br) tracer was applied on 3 December 2012. The second irrigation advanced over the lysimeter on 4 December 2012 at 08:28 h. The first tracer drainage sample was collected at 11:30 h. A total of six sample sets were collected on 4 December, two on 5 December, one on 6 December and one on 17 December.

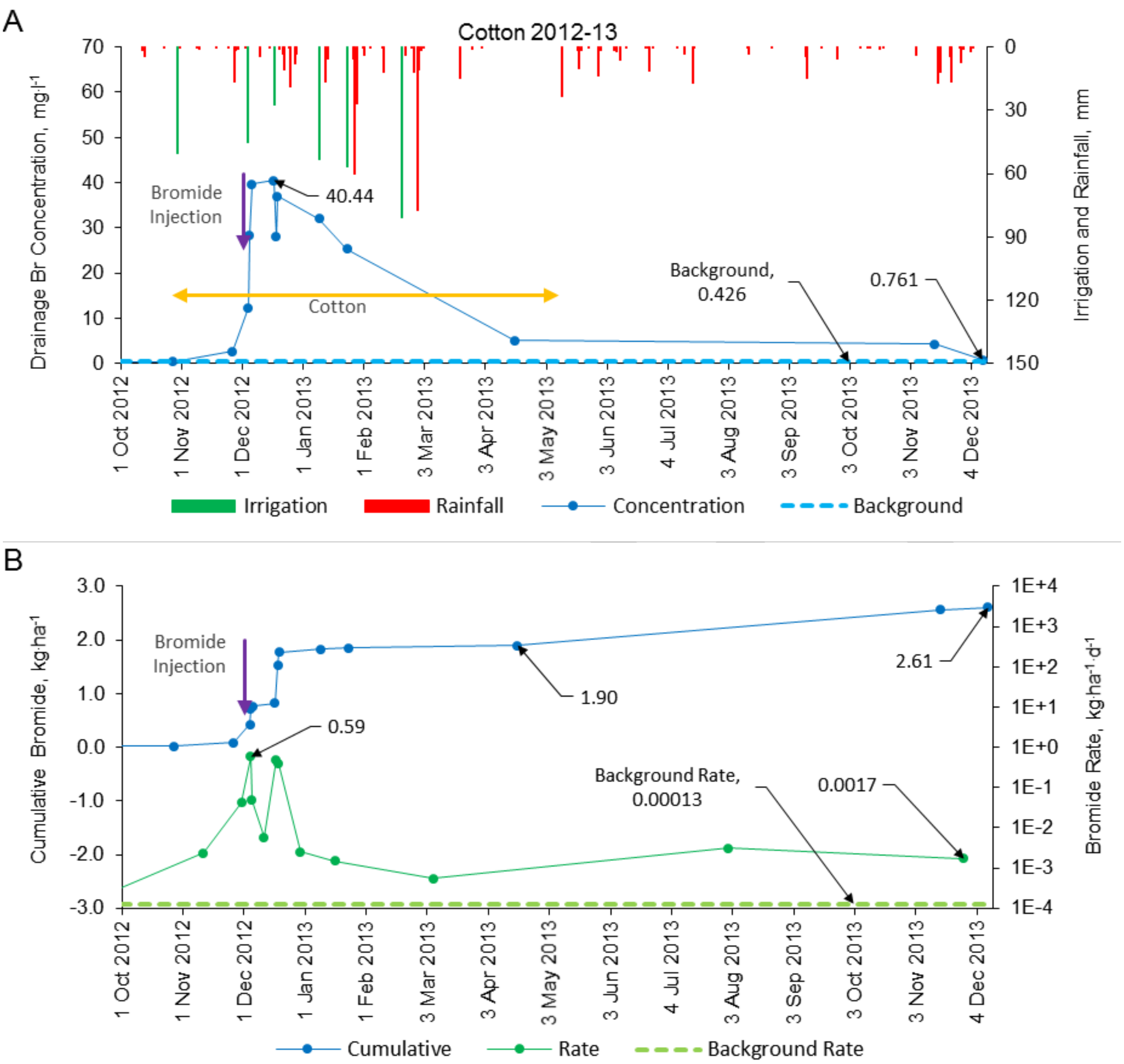

Figure 10. A) Drainage bromide concentration, daily volume weighted (left axis) and rainfall and irrigation (right axis). B) Cumulative bromide recovered in drainage, daily volume weighted (left axis) and daily bromide recovery rate (right axis).

The third irrigation advanced over the lysimeter on 18 December 2012 at 07:30 h. The first drainage sampling was at 10:45 h. Four sample sets were collected on 18 December, one on 19 December, and one on 9 January 2013. The drainage accumulation rate was only sufficient for 2 further sample events during the irrigation season.

The bromide concentration seven days before the tracer injection was 2.687 mg/l, significantly greater than the background level of 0.426 mg/l is unexplained (Fig. 10A). The volume weighted bromide concentration was 22.46 mg/l in the first sample on 4 December, indicating that this water had by-passed the root zone and transited the sub-soil to a depth of 2.1 m in less than 3 hours. During that day subsequent Br concentrations decreased to pre-irrigation levels then increased back again. The volume weighted Br concentration on the day of the irrigation was 12.38 mg/l (Fig. 10A).

Daily volume weighted concentrations continued to increase over the next two weeks before beginning to slowly decrease over the remainder of the irrigation season. However, Br concentrations remained elevated above background levels for a further 7 months during the fallow before returning to background concentrations in December 2013.

Fig. 10B shows the rate of bromide removal in drainage (i.e. the actual amount rather than the concentration) had peaked twice, once after the second irrigation (when it was applied) and once after the third. After this there was a much lower rate of removal, but still greater than the background rate. The two peaks suggest that easily accessible water in the surface layers was completely exchanged in two irrigations, with some draining rapidly via bypass flow. The remainder flowed more slowly as matrix flow resulting in the small but long-lived Br removal rate over the subsequent year.

The total bromide recovery was 2.61 kg/ha over 369 days since application (Fig. 10B), 0.74% of the applied Br. Of this 1.83 kg/ha was during the first 35 days. Despite the low final Br drainage concentrations, the final recovery rate was still an order of magnitude greater than background recovery rates. Any Br that had not been removed in irrigation runoff or taken up in plant biomass would still be distributed in significant concentrations in the soil.

4.3.2 Fate of nitrogen

The seasonal nitrogen inputs and drainage losses for the 2011-12 corn and 2012-13 cotton, over 26 continuous months, are summarised in Table 4. The 2011-12 corn crop was planted in 19 September 2011 and received two irrigations, on 28 September and 11 November, prior to the fertilizer application. On 15 December 2011 180 kg/ha of nitrogen was applied as broadcast urea. This was followed by adequate rainfall prior to the third and final irrigation on 10 January 2012, with subsequent rainfalls adequate for completion of the short-season corn.

Table 4: Nitrogen applications and drainage recoveries during, 2011-12 corn/fallow and 2012-13 cotton fallow periods.

Crop	N application as urea	Drainage NO_3-N	Drainage TN	NO_3-N Loss	TN Loss
	kg/ha	kg/ha	kg/ha	%	%
Corn 2011-12	180	0.151	0.513	0.10	0.34
Fallow 2012	0	0.033	0.097		
Cotton 2012-13	160	1.487	2.029	1.51	2.16
Fallow 2013	0	0.936	1.424		
Total	340	4.088	6.727	0.70	1.16

Total nitrogen (TN) includes nitrate nitrogen (NO_3-N) and all dissolved organic nitrogen (DOC) compounds. The TN lost was relatively small, only 0.34%, with NO_3-N less than a third of all N losses that season. While most of the absolute N losses occurred during the corn crop, fallow N losses relative to drainage were proportionally greater. The 0.5 mm of fallow drainage was 14% of that during the preceding corn, but the fallow TN and NO_3-N losses were 19% and 22%, respectively. Not only were there organic and inorganic nitrogen compounds available following the corn crop, but the fallow leaching efficiency was also greater.

The 2012-13 cotton crop was planted on 27 October 2012 and received two irrigations, on 30 October and 4 December 2012 prior to fertilisation. On 12 December 2012 there was 160 kg/ha of nitrogen applied as broadcast urea. This was followed by a further four irrigations on 18 December 2012, 10 January 2013, 24 January 2013 and 21 February 2013.

High frequency drainage sampling was conducted during this season. Daily volume weighted cumulative NO_3-N losses and loss rates are shown in Figs 11A and 11B. Although there were two irrigations prior to the urea application there were significant NO_3-N concentrations and fluxes in the drainage from these irrigations. Sufficient nitrate had mineralised during the preceding fallow and early part of the cotton season to meet crop demands while also being susceptible to leaching.

NO_3-N concentrations and loss rates declined only slightly prior to rebounding following the urea application and third irrigation. Concentrations and losses declined until the end of the season. NO_3-N concentrations rebounded at the end of the season due to soil drying following the final irrigation with little rainfall with low but consistent fluxes continuing through the fallow.

Nitrogen compounds continued to be lost in drainage during the fallow period following the cotton crop, as happened during the previous corn crop, although drainage volumes and N losses were both greater in the cotton crop. There was greater drainage during the fallow, 16.9 mm, than during the cotton season, 13.1 mm. Absolute nitrogen losses during the fallow were less than during the cotton crop, but were not insignificant. The fallow TN and NO_3-N losses were 70% and 63%, respectively, of the cotton season losses.

Nitrogen drainage losses in the corn season were much less than the cotton season losses, which may be partially attributed to the very different plant biomasses and lengths of growing season. The 2.2% TN and 1.5% NO_3-N losses in the 2012-13 cotton was much less than comparative losses of 10% TN and 5.9% NO_3-N in the 2008-09 cotton crop, the greatest cotton losses measured to date.

4.3.3 Salt

The 2012-13 drainage EC levels show a typical response pattern. High EC levels were present at the end of the fallow, 9.7 dS/m for the volume weighted average of all trays, with individual trays as much as 18.2 dS/m, roughly 36% of the EC of seawater. The EC levels gradually decreased during the growing season due to leaching and dilution from irrigations and rainfalls. EC levels then rebound again during the following fallow. For comparison the typical irrigation water EC is approximately 0.4 dS/m. The drainage pH values, not shown, ranged between a minimum of 8.94 to a maximum of 12.02. For comparison the irrigation water has a typical pH of approximately 8.3.

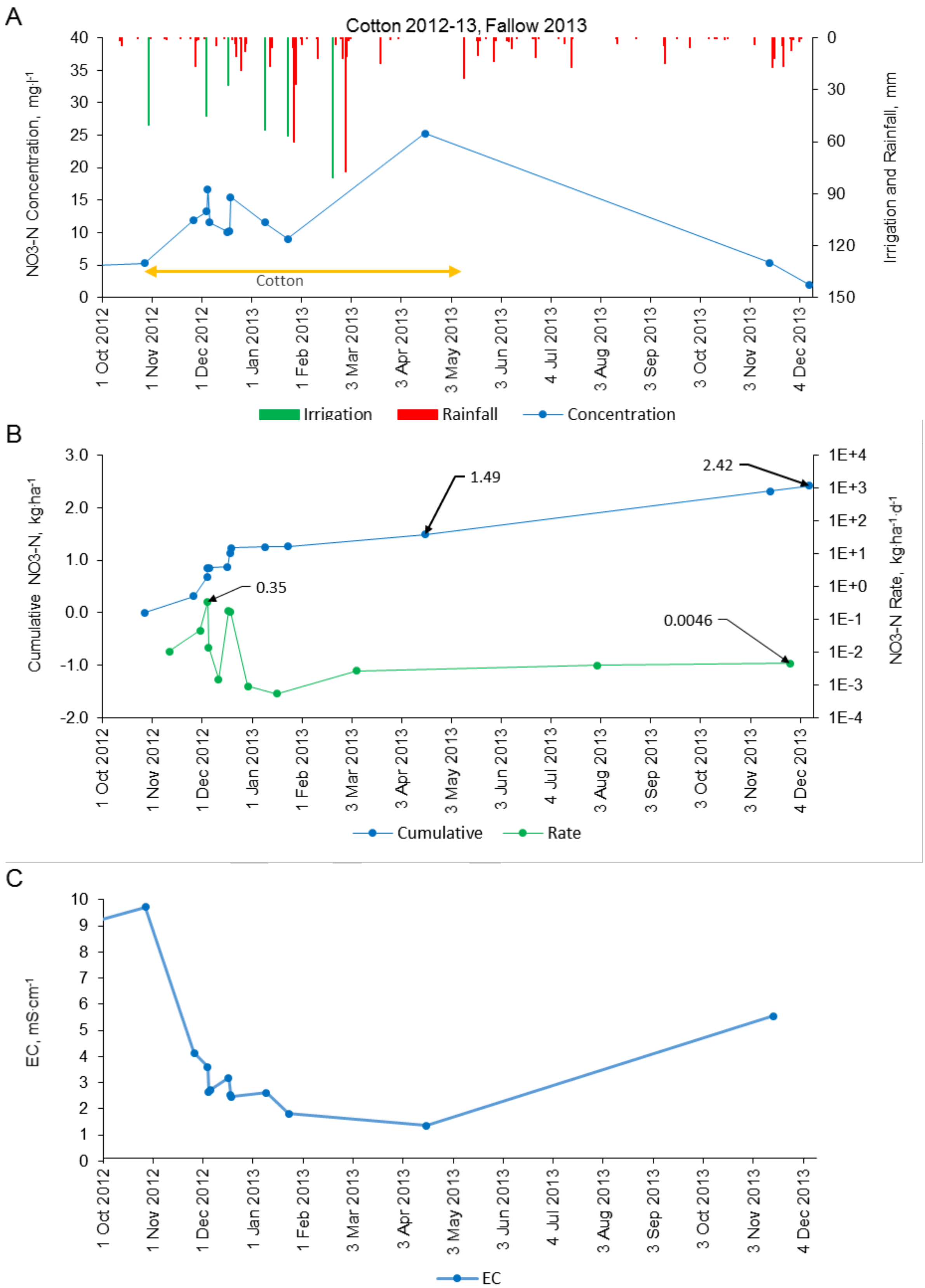

Figure 11. A) NO_3-N concentration in drainage. B) Cumulative NO_3-N collected in drainage. C) Drainage EC

4.4 OJECTIVE 4: IMPROVE THE APSIM CROP MODEL.

- **Milestone 4.1 Conceptual water balance model for cracking clays formalised for use in APSIM.**

Conceptual model

During previous projects involving the ACRI lysimeter, observations of deep drainage, soil water suction and calculated gradients, along with video evidence of the advance of a furrow irrigation front, have led to a conceptual model for soil water dynamics in this cracking clay soil that distinguishes two different flow situations:

- During 'normal' rainfall water infiltrates reasonably uniformly and the wetting front slowly advances to depth. When it reaches 2.1m drainage occurs (e.g. fallow 2009-10; see Fig. 12).
- During furrow irrigation, water preferentially enters the cracks and other macropores. The upper 0.5m is very porous and well connected with the macropores and wets as soon as the irrigation front reaches. From 0.5-1.0m there are fewer macropores and exchange between macropores and the soil matrix is slower. This more pronounced below 1m where there are few macropores, most of which are slickensides (Fig. 14). Irrigation reaching macropores below 0.5 m bypasses the soil matrix and rapidly becomes deep drainage (Fig. 13). This behaviour can be represented in a conceptual diagram (Fig. 14).

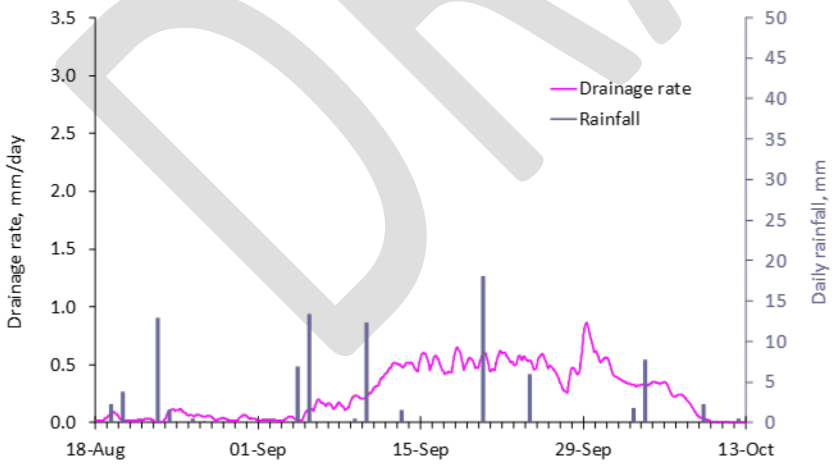

Figure 12. Drainage rate measured by the lysimeter during 2009-10 fallow.

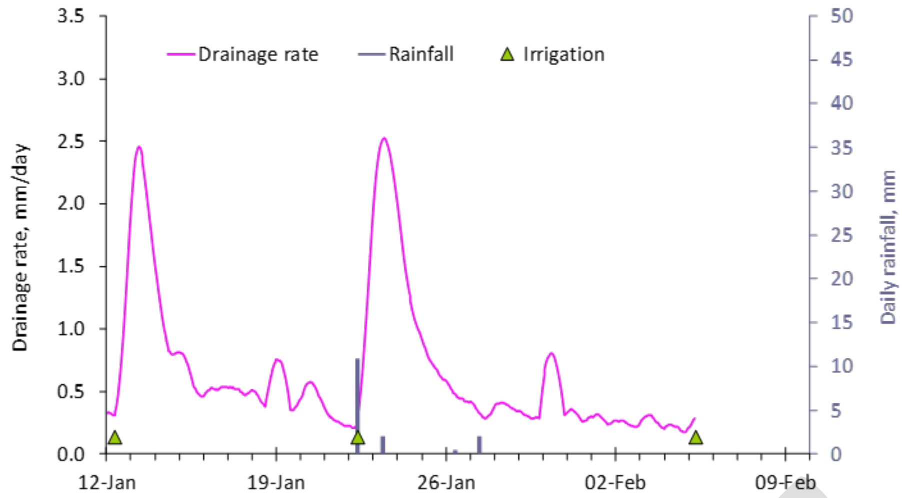

Figure 13. Drainage rate measured by the lysimeter during the 2008-09 cotton season.

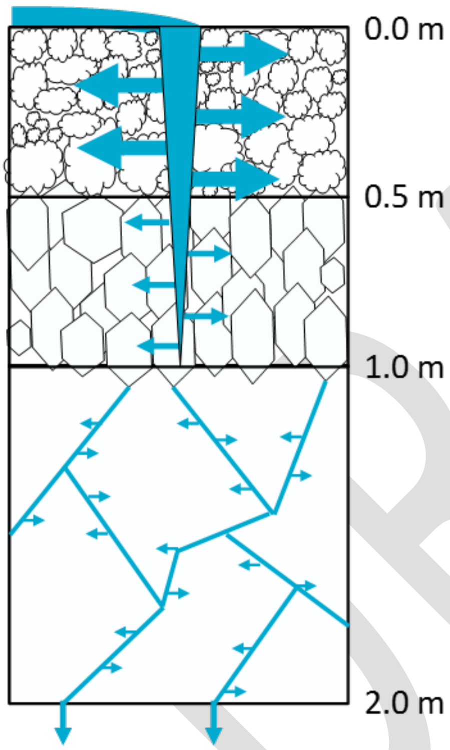

Figure 14. Conceptual diagram of bypass flow during furrow irrigation.

Modelling approach

To build on the conceptual model reported previously, the use of the APSIM farming systems model to model the water balance under cotton was investigated during the reporting period. While there are models of dual permeability flow (fast flow through macropores and slow flow through the soil matrix), the initial attempts at modelling focussed on a simpler, 1 dimensional model – APSIM with the "tipping bucket" soil water model SoilWat. The APSIM model is widely used in agricultural systems analysis in Australia and would likely be a future tool of choice for analyses of fertiliser and irrigation management in cotton too. It is also currently the only model integrated with the cotton model developed and tested at ACRI. The more complex models like Hydrus 2D do not simulate crop growth nor the interactions of the crops with the soil system (water and nitrogen) and agronomic management.

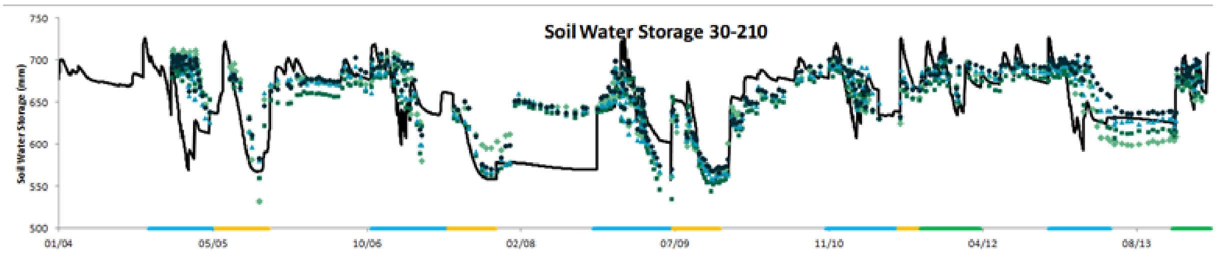

Figure 15. Observed (symbols, from 4 NMM measurements) and predicted (line) soil water storage between 30 and 210 cm depth (surface soil affected by 2-dimensional ridging). Colours on the x-axis indicate cropping seasons: blue = cotton, yellow = wheat, green = maize, no colour = fallow.

The SoilWat model is a tipping bucket model, in which soil layers fill up with water in response to infiltration of rainfall and irrigation and water flows to the next layer when a layer is full. In reality, the SoilWat model has some additional features that allow water to drain and redistribute in the days following rain, as well as simulating evaporation. For details see www.apsim.info.

Although the data suggest that this 1-dimensional model might struggle to capture the processes under furrow (flood) irrigation, it was decided to investigate its abilities and limitations and possibly identify simple model adaptations.

Modelling process and progress

The modelling process involved gathering all available data for input, such as rainfall, irrigation, temperature, solar radiation, crop management and fertilisation to see if the model could simulate what happened at the lysimeter site.

A simulation of the complete sequence of crops was set up as well as irrigation and fertiliser management applied to the lysimeter from the 2004-05 cotton crop through to the 2013-14 maize crop (see coloured bars on x-axis in Fig. 15). As the crops come and go, they leave the water and nitrogen behind in the soil ready for the next season. The ultimate aim is to be able to simulate the complete sequence without resetting the model at any point. However, initially it helps to apply resets at the start of different seasons to avoid compounding errors so that model performance can be analysed for individual seasons. Data presented in this report use these seasonal resets.

Overall the predicted soil water storage for the profile compared reasonably well with the storage calculated from the collected neutron moisture meter (NMM) data (see Fig. 15) similar to other model verifications of agronomic models focussed on soil water storage. However, predicted drainage is very sensitive to small deviations in soil water storage. The following problems were identified:

- The sequence included five cotton crops (see blue bars on x-axis in Fig. 15), whose soil water dynamics varied significantly. In some seasons there was uptake from layers as deep as 1.8 m, whilst in others the crop did not even use all the water at 1.2 m depth. The model was not been able to simulate these differences and had a tendency to use water from depth earlier than observed. We checked whether crop observations from the paddock show whether the parameterisation of crop phenology and growth is correct, or whether we need to look more closely at the root growth and/or soil water uptake routines.
- During the fallow of 2008-09 it failed to capture the sudden wetting up due to summer rain in January 2009. During the fallow of 2009-10, the opposite happened – rainfall input to the model is higher than the increase in soil water storage suggests. We checked rainfall inputs and runoff predictions. One problem is that rainfall at this time of the year can result from summer storms and be intense, causing surface sealing and creating significant runoff. The SoilWat model simulates runoff using a curve number approach. This approach was developed to get runoff levels correct on average over a large number of events, but may not capture specific individual events.

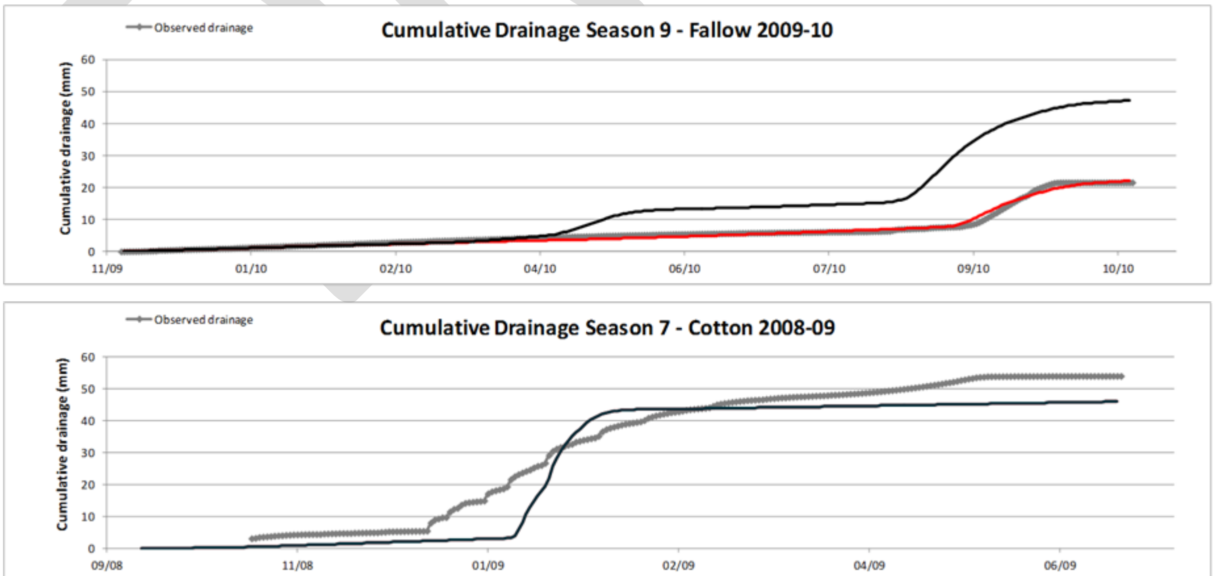

Figure 15. Observed (grey symbols) and predicted (black line) cumulative drainage during the 2009-10 fallow, and 2008-09 cotton season. Red predicted line had reduced rainfall input during summer storm on 22/12/2009 (see Fig. 10 and text).

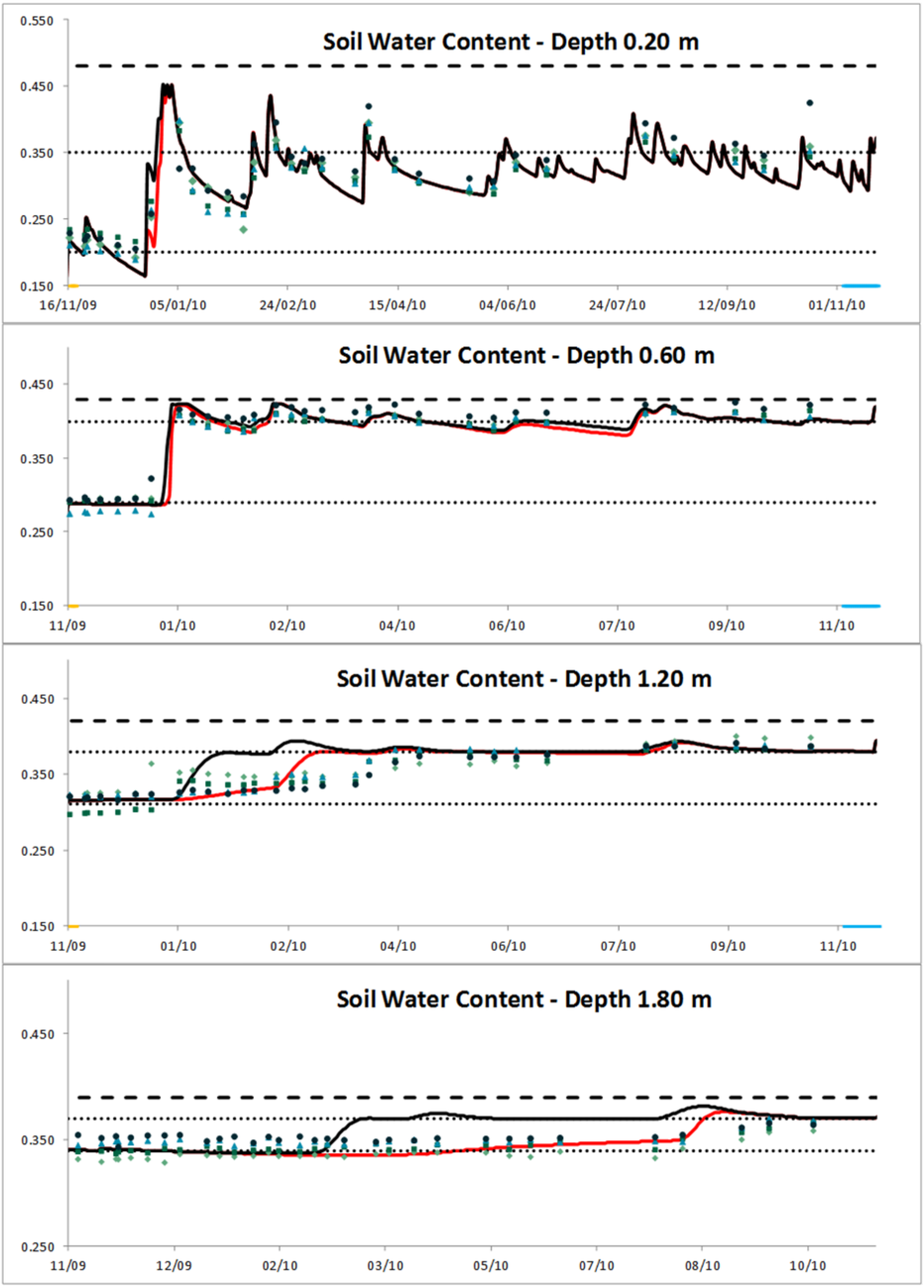

Figure 16. Observed (symbols, 4 NMM measurements) and predicted (lines) soil water content at different depths during the 2009-10 fallow. Black line: prediction with rainfall from rain gauge; red line: prediction which excluded part of the rainfall on 22/12/2009 due to it not being recovered in the soil (model under predicted sealing effect and resulting increased runoff from this sudden, intense summer storm)

The impact on drainage from the underestimation in runoff and overestimation in infiltration during just one 54 mm event on 22/12/2009 is shown in Fig. 16. The excess water appears as an over-prediction in drainage, albeit a couple of months later. Fig. 17 shows how the water is gradually moving (cascading) through the profile. The over-prediction of infiltration (and hence soil water storage) in late December causes water to arrive at the bottom of the profile too early. Evaluation of the NMM data suggests that there was only an increase of about 26 mm in soil water storage. If the amount of infiltration is reduced and extra runoff generated, the prediction improves significantly (Fig. 16).

Another focus was to explore the soil water dynamics under cotton in conjunction with the prediction of cotton phenology and biomass growth as provided by the APSIM Cotton model component. It was also anticipated that the analysis would provide an ideal platform on which to compare the performance of the stand-alone OZCOT model to that of APSIM-OZCOT. The latter has interfaces with more diverse science modules included in APSIM for soil water, infiltration, runoff, etc. while the former has a more limited feature set, but is highly tuned to the soils in which the lysimeter is located.

The lack of in-season observations of the crop posed a significant problem to fulfilling this objective. The trials were conducted with records of sowing, fertilising, irrigating and harvesting, along with biomass and yield data at harvest. To attempt to analyse the model performance and compare it to observed readings of soil water, it would be essential to have confidence that the crop growth was simulated quite accurately, with phenological stages of emergence, first square, first flower, first open boll, and maturity (60% bolls open) being well matched to observed dates, as well as LAI measurements throughout the season. As there are no observation recorded apart from defoliation and harvest, it is impossible to be as confident about the growth of the simulated crop.

Table 5 shows the variations in predicted maturity date and yield between the standalone OZCOT, APSIM-Cotton and observed values. While ‘tuning’ of the model input parameters can reduce the discrepancies in yield and maturity date, the underlying problem of not knowing how the crop growth is tracking during the season cannot be resolved. Questions would always remain over any detailed soil water usage analysis without detailed crop observations to match them against.

Table 5: Comparison of model timing and yield prediction

Source	Sown	Maturity/Defoliation	Yield (kg/ha)
2006-07 Cotton			
Observed	19 Oct 2006	4 Apr 2007	2700
APSIM-Cotton	19 Oct 2006	15 Mar 2007	2115
Standalone OZCOT	19 Oct 2006	19 Apr 2007	2640
2008-09 Cotton			
Observed	9 Oct 2008	18 May 2009	2900
APSIM-Cotton	9 Oct 2008	20 Mar 2009	2250
Standalone OZCOT	9 Oct 2008	23 Mar 2009	2610
2010-11 Cotton			
Observed	4 Nov 2010	15 Apr 2011	1500
APSIM-Cotton	4 Nov 2010	2 Apr 2011	2160
Standalone OZCOT	4 Nov 2010	10 May 2011	2350
2012-13 Cotton			
Observed	25 Oct 2012	11 Apr 2013	2400
APSIM-Cotton	25 Oct 2012	7 Mar 2013	2220
Standalone OZCOT	25 Oct 2012	14 Mar 2013	2310

Analysis of model logic

In the absence of good crop data to benchmark model performance against, it was decided to review the logic used for water extraction in the two versions of the model – standalone and APSIM-Cotton.

While the interaction between the different APSIM components (SoilWat, mvOZCOT and met) did yield slightly different soil evaporation and plant evaporation values in APSIM when compared with standalone OZCOT, the routine used to extract the required water from the soil layers was exactly the same in both versions of the model. The equations used in this routine were developed by Brian Hearn based on data obtained from cotton grown on soils in Chico block at the Myall Vale research station, the same block where the lysimeter is located. Based on this it is reasonable to predict that the water extraction (Fig. 17) would be a very close match to reality for this soil. The routine utilizes two extraction curves, one for drier soils (soil moisture index, SMI, of 0.3 and below) and one for soils moister than SMI 0.3, as shown for SMI = 0.7. Both curves are very similar and show a bias to extraction from surface layers – when available – with extraction from drier soils slightly more biased towards deeper layers.

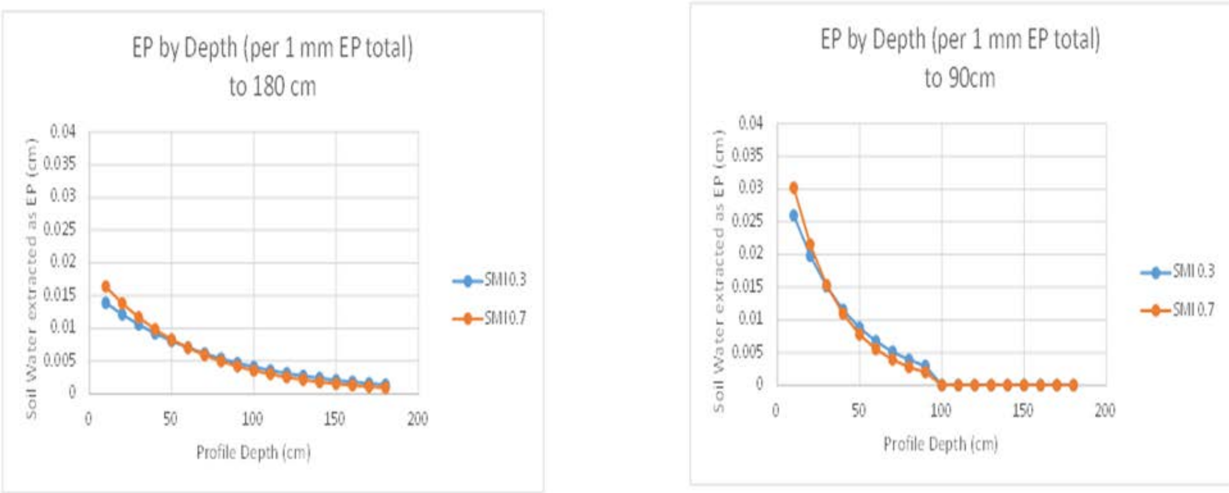

Figure 17. Water extraction curves: EP (evapotranspiration) by depth down profile for two soil depths (left: 180 cm; right 90 cm).

Limitations with pre-set extraction curves

While the water extraction by the crop has been shown to be very adequate for modelling purposes over many years, there are clear limitations to its applicability. Traditionally cotton has been grown on high clay content, deep profile soils, similar to those used to develop these soil water extraction curves, and so the extraction patterns have been adequately modelled. But with the need to model cotton crops growing on more diverse soil types, it can be expected that the limitation of extraction patterns of one soil type only will become a problem.

APSIM crop components generally utilize a flexible and definable extraction regime which is calibrated using '*kl*' and '*xf*' factors. These factors define how the roots grow through the soil profile and how accessible the water in the profile is to the crop. Limited work has been done on establishing cotton '*kl*' values for differing soil types. Initial investigations have found '*kl*' values reported for heavy clay soils in the range of 0.06 to 0.1.

The necessary modifications to APSIM require implementing a change to utilizing '*kl*' values and water extraction by cotton based on them has been completed. As well the development of *xf* value functionality is currently under way. As this is considered a change in the science of the model, a fairly extensive review process and sound validation data sets are required before such changes can be submitted to the APSIM Initiative for consideration of inclusion into the modelling system.

Outcomes

5. Describe how the project's outputs will contribute to the planned outcomes identified in the project application. Describe the planned outcomes achieved to date.

Scientific: Improved ability to predict water movement in heavy clay soils including quantification of by-pass flow.

Industry/applied: Better understanding of the magnitude of drainage. Better understanding of the situations that trigger drainage leading to better tactics to reduce it.

- The pattern of drainage during this reporting period was broadly similar to that found in previous projects using the ACRI lysimeter. The greatest drainage rates occurred immediately after early irrigations when soil water deficits were small. However, the very large drainage rates reported from earlier project, such as the 2008-09 cotton season, were not repeated during this reporting period. This was because of the build-up of compaction over the lysimeter, which was also previously reported for the 2010-11 cotton crop, immediately before this reporting period.
- After these drainage peaks drainage continued at lower rates after between irrigations. After irrigations later in the season, peaks in the drainage rate were not discernible, but there was continuous drainage at lower rates.
- Drainage under irrigated corn (2011-12), 3.6 mm, was less than under cotton (2012-13), 13.0 mm.
- Whist the peak drainage rates generally occurred during the irrigation seasons, there was significant drainage during the longer fallow periods, as reported for during earlier projects. There was 16.9 mm of drainage during the fallow following the 2012-13 cotton crop which was similar to that reported before for the 2009-10 fallow. These represent mean drainage rates of 0.078 and 0.062 mm/day. The mean drainage during shorter fallow periods was an order of magnitude smaller.
- The bromide tracer experiment found that bromide applied immediately before the second irrigation of 2012-13 cotton appeared in drainage at 2.1 m depth within 3 hours of irrigation.
- The flux of bromide in drainage was still above baseline one year after injection.
- The results confirm that drainage occurs in two forms, bypass drainage and matrix drainage. Bypass drainage occurs immediately following the presence of large amounts of free water following furrow irrigation, as shown by the bromide tracer experiment. This results in peaks in the drainage rate in the days following irrigation. Bypass drainage is mitigated by the soil water deficit in the subsoil, especially 0.5-1.0 m depth. As the season progresses, crop water use creates larger deficits in the subsoil between irrigations which absorbs some

of the bypass flow. Matrix drainage occurs when wetting fronts move through the soil profile as rain is stored during prolonged fallow periods. During shorter fallows, there is insufficient time for the wetting front to travel to 2.1 m depth. Matrix flow also results in the lower rates of drainage that occur between irrigation once the peak drainage rate has subsided.

- The bromide tracer experiment points to complex multiple pathways that water takes through the soil. A portion of each irrigation travels rapidly to depth and becomes drainage when the soil water deficit of the subsoil is not great enough to absorb it. Another portion travels rapidly by bypass flow into subsoil, but is absorbed into the soil matrix, to appear later as matrix flow. Yet another portion enters the subsoil from above as matrix flow will pass more slowly through the profile before it appears as matrix drainage. It is possible that this portion is responsible for the low recovery of bromide during the experiment.
- Drainage rates are very susceptible to soil physical condition, in particular compaction.

Scientific: Improved ability for researchers to simulate the long-term water balance of cracking clay soils and to explore the impacts of different cropping systems and climates on water use efficiency and drainage losses.

Industry/applied: Ability to assess potential management tactics to improve water use efficiency.

- The conceptual drainage model derived previously has been broadly confirmed, as described above.
- The APSIM farming systems model using the SoilWat water balance module was used to simulate soil water and drainage during the seasons of this and earlier reporting periods, but was unable to do so correctly.
- One problem was the partitioning of heavy rainfall into infiltration and runoff.
- Another problem was the need to correctly simulate root growth and water extraction using *kl* and *xf* factors. The need to incorporate these factors into the cotton module used in APSIM was identified. Introducing the functionality of *kl* into the cotton module has been completed but requires field verification. Development of *xf* functionality for the cotton module is in progress.

Scientific: Improved quantification of diffuse recharge (i.e. not related to recharge from rivers), its relationship to deep drainage and the time scale over which the relationship operates. This will improve catchment groundwater modelling by reducing uncertainty of diffuse recharge (a relatively small flux but multiplied by a large area).

Industry/applied: Better quantification of the risks to groundwater posed by drainage under irrigated cotton including rising watertables and contamination of deeper aquifers. This information can help catchment managers improve catchment management.

- A method was developed to use the piezometer data at the lysimeter facility to estimate recharge into the unconfined aquifer. This involves separating the effects of phreatic leakage between the unconfined and confined aquifers from the overall rate of change of the head of the unconfined aquifer.
- No correlation was found between groundwater recharge and lysimeter drainage or irrigation infiltration in the lysimeter field due to measurement scale.
- There was an overall correlation between groundwater recharge and rainfall for entire data set.
- The correlation of groundwater response with rain but not irrigation/drainage, together with the recharge rates being much greater than lysimeter drainage rates suggests the unconfined aquifer is responding to a larger area than the lysimeter field, possibly receiving drainage from main tailwater channel, and/or main supply channel.
- The correlation of recharge with large rainfall events or floods over short intervals may indicate by-pass flow through 16m clay vadose zone with 90 day lag in peak flow rate response.
- More than one summer seasonal rainfall may accumulate in vadose soils moving under slow matrix flow before reaching aquifer as attenuated recharge rate fluctuations.

Scientific: Quantification of losses of nitrogen and carbon in drainage which is essential for greenhouse gas researchers to be able to close the nitrogen and carbon balances. Improved interpretation of water balance results in terms of the flow paths that result in drainage. Assessment of changes to soil chemistry and whether they are likely to affect sustainability.

Industry/applied: Knowledge of the effects of irrigation using different water sources on soil salinity and sodicity and the risks changes pose to sustainable use of soil. Development of ways to more accurately calculate the necessary leaching fraction to prevent salinity.

- A bromide tracer experiment was carried out to improve understanding of flow paths in the soil profile, as described above
- The losses of nitrogen during the cotton crop were less than in previous cotton seasons, due to lower overall drainage.
- Nitrogen loss was found to continue during the fallow after irrigation season.

- Total nitrogen and nitrate nitrogen losses were found to occur prior to fertilizer application due to presence of dissolved organic nitrogen (DON) and NO3-N mineralised from DON.

6. Please describe any:-
   a) technical advances achieved (eg commercially significant developments, patents applied for or granted licenses, etc.);
   b) other information developed from research (eg discoveries in methodology, equipment design, etc.); and
   c) required changes to the Intellectual Property register.

- A novel method was developed to estimate recharge into the upper, unconfined aquifer from piezometer head data for the unconfined aquifer and the confined aquifer below it.
- The use of barometric efficiency to infer the degree of saturation in the vadose zone was explored.

Conclusion

7. Provide an assessment of the likely impact of the results and conclusions of the research project for the cotton industry. What are the take home messages?

Extension Opportunities

8. Detail a plan for the activities or other steps that may be taken:
   (a) to further develop or to exploit the project technology.
   (b) for the future presentation and dissemination of the project outcomes.
   (c) for future research.

9. A. List the publications arising from the research project and/or a publication plan. (NB: Where possible, please provide a copy of any publication/s)

Ringrose-Voase AJ, Nadelko AJ (2013) Deep drainage in a Grey Vertosol under furrow-irrigated cotton. Crop and Pasture Science 64, 1155-1170

Macdonald B, Ringrose-Voase AJ, Nadelko AJ, Farrell M, Tuomi S, Nachimuthu G (2016) Dissolved organic nitrogen contributes significantly to leaching from furrow irrigated cotton-wheat-maize rotations. Soil Research 54. (in press)

B. Have you developed any online resources and what is the website address?

No

Part 4 – Final Report Executive Summary

The variable tension lysimeter facility at ACRI was used to investigate deep drainage below the root zone under a furrow irrigated cotton rotation on a Grey Vertosol. The results built on findings from earlier research using the facility. Unfortunately, the data acquired by the lysimeter towards the end of the project was unusable due to a series of equipment failures as the facility ages and problems due to compaction over the lysimeter trays. However, the results were enhanced by a bromide tracer experiment carried out during the second irrigation of the 2012-13 cotton season.

Drainage occurs in two forms: bypass drainage and matrix drainage. Bypass drainage occurs rapidly immediately after irrigations when water flows down macropores from the surface bypassing the subsoil matrix and exiting the root zone. Bypass drainage starts within 3 hours of irrigation and results in peaks in the drainage rate that last for a few days. The fact that this drainage has bypassed the soil matrix was confirmed by the bromide tracer experiment in which the tracer appeared in drainage in under three hours from irrigation. Bypass drainage is reduced when the soil water deficit in the subsoil, especially 0.5 – 1.0 m depth, is greater, as some of the flow is absorbed into the subsoil matrix. This occurs later in the irrigation season as crop water use creates larger and larger subsoil deficits between irrigations. For this reason, most bypass drainage occurs after early irrigations.

Matrix drainage occurs when water travels through the soil profile in the matrix. It occurs at lower rates than bypass drainage and does not result in peaks in the drainage rate, but continues over periods of weeks or months. It is caused by the build-up of rainfall in the soil generally when water use is low such as during fallow periods. The build-up causes a wetting front to move through the soil profile until it exits the root zone as drainage.

The bromide tracer experiment suggested there are complex, multiple pathways by which water can travel though the profile to become drainage. A portion of irrigation water can travel directly through macropores to become drainage within a few hours. Another portion travels down macropores but is absorbed by the subsoil and appears later as matrix drainage. Final portion enters the subsoil from above and travels slowly through the soil profile and only becomes matrix drainage if it is not used by the crop first.

The amount of bypass flow during this project never reached the amounts reported for previous projects due to the build-up of compaction over the lysimeter, suggesting that bypass drainage is very susceptible to soil structure damage.

It was found that drainage resulted in the loss of nitrogen both as nitrate and as dissolved organic nitrogen and that losses continue during fallow periods. The amounts of nitrogen lost were generally less than previously reported due to the smaller drainage amounts.

A method was developed to estimate to use the piezometer data to estimate recharge into the unconfined aquifer from the vadose zone. Recharge was not correlated to drainage at the lysimeter, nor to irrigations in the lysimeter field, due to differences in the scale at which they operate. However, recharge was correlated to rainfall over longer periods. Its magnitude was greater than drainage rates from the lysimeter which suggests that other sources of drainage – for example from channels and storages may be more important. Most of the time phreatic leakage occurred from the unconfined to confined aquifer due to extraction from the latter for irrigation, with the possibility of bringing contaminants from the unconfined aquifer into the confined one.