Cotton Catchment Communities CRC

Project 2.01.02

Final Report

Capturing our understanding of soil water balance and deep drainage under irrigation in models

Queensland Murray Darling Committee

UNSW

Condamine Alliance PEOPLE WATER LAND WILDLIFE

Queensland Government

FINAL REPORT

Part 1 - Summary Details

Cotton CRC Project Number: 2.01.02

Project Title: Capturing our understanding of soil water balance and deep drainage under irrigation in models - a basis of design of efficient farming and for assessing impacts on catchments

Project Commencement Date: 01/01/2007 **Project Completion Date:** 31/12/2010

Cotton CRC Program: Program 2

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Abbreviations and acronyms

BG-CMA	- Border-Gwydir Catchment Management Assoc.
CA	- Condamine Alliance (NAP Regional Body, Toowoomba)
CCC CRC	- Cotton Catchments Communities Collaborative Research Centre
CRDC	- Cotton Research and Development Corporation
DERM	- Department of Environment & Resource Management
DPI&F	- Department of Primary Industries and Fisheries (Qld)
LWMP	- Land and Water Management Plan
NRW	- Natural Resources and Water, Queensland (now DERM)
QMDC	- Queensland Murray-Darling Committee
PAWC	- plant available water capacity
UNSW	- University of NSW
USQ	- University of Southern Queensland
UTS	- University of Technology Sydney (a participant in the CCC CRC)

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Final Report

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1. Executive summary

The cotton industry and other investors have spent millions of dollars on 'water balance' related research over the past two decades. While **soil water balance models** can be used today to answer critical questions affecting the industry, little of this water balance research has been fully captured or insufficient data are available to model these sites. A lack of basic soil physical data limits the use of water balance models across many areas of the cotton industry.

Models are commonly used as decision support tools in agriculture. This project captured data from various past and current studies of water balance and deep drainage under irrigation in N NSW and Qld in a form useful for modelling, and 'filled in' some to the gaps with additional soil hydraulic measurements at key sites. These data were used to test the models, derive parameters, enhance understanding and so provide insights across landscapes and over longer time periods, especially in CRC groundwater/catchment modelling studies.

Electromagnetic Induction (EM38) technology (with depth slicing) was developed and used throughout a cotton growing season to monitor soil water at a range of depths and provided input to the model HowLeaky (Mills et al. 2008). The data agreed to a large degree with the model, which estimated that during two periods in the season, a significant amount of deep drainage occurred (100 mm). This is of concern both in terms of wasting water and potential groundwater recharge.

Geophysical surveys and deep soil coring were taken in both irrigated and uncleared landscapes throughout the Condamine (co-funded by Condamine Alliance) and Border Alluvia (co-funded by Border-Gwydir CMA), to define the moisture status below the root zone. That is, is there a moisture deficit buffer which can store increased deep drainage from irrigation or is the regolith nearly full? Transects imaged across naturally vegetated landscapes into irrigated paddocks found all soils under native vegetation to be very dry (low conductivity) even when only sparsely populated by trees. In contrast, significant long-term migration of water has occurred to deep within the regolith (up to 15 m) in most irrigated paddocks. A wet (close to saturated) zone was found in the upper 6 m of soil in the irrigated paddocks. The imaging results confirmed that the unsaturated zone is filled to near saturation under all irrigated sites and remains very dry under all native vegetation sites. Deep coring has also be used at a number of sites to collect data to improve geophysics model parameterisation for clay soils, so that resistivity imaging can be used with more confidence in the future to estimate the amount of water to deep in the soil regolith.

Finally, a **monitoring bore network** was installed across the Border-Moonie catchments to allow continued observation of groundwater behaviour in irrigated and dryland areas. This area was found to have a high potential risk of future salinity problems but had little monitoring installed. A "20-point plan" was developed and has been funded in stages by NRM Regional Bodies (QMDC & Border-Gwydir CMA) and DERM.

Contact details for more information: DERM, Toowoomba, Jenny Foley, Mark Silburn, Andrew Biggs.

2. Background

Water is becoming an increasingly limited resource and losses of water to runoff and deep drainage may have adverse consequences. A review of available data indicates that considerable deep drainage can occur under past/current irrigation practices (Silburn & Montgomery 2004). Modelling of soil water balance is now used systematically to estimate deep drainage in spatial salinity risk assessment in Queensland, NSW and Victoria (e.g. Yee Yet & Silburn 2003). A number of projects have measured deep drainage in dryland cropping, pasture and woodlands, and irrigated cropping in northern NSW and Queensland (e.g. RWUE, CRDC, GRDC, MDBC projects).

To ensure confidence in the modelling, various models have been tested against measured drainage **in dryland cases** and this is continuing in several projects (e.g. DERM, Owens et al. 2003, 2004). However, **little of the large amount of data for drainage or runoff under irrigation has been used to test and inform models**, even models commonly used in the industry (e.g. OZCOT and HydroLOGIC). Much of this measured data will eventually be, or has already been, lost.

The cotton industry and other investors have spent millions of dollars on 'water balance' related research over the past two decades. However, little of this work can be used today to answer critical questions affecting the industry. Studies have generally addressed single components of the water balance (ET, runoff or deep drainage), for a season or two, under a specific set of conditions (soil A, irrigation management Y, etc). Published papers (a few) and mostly 'grey literature' reports can give a 'feel' for the water balance issue studied, however these results are easily dismissed as location specific; 'it only happens in the Macquarie'. In contrast, in dryland cropping and pasture lands, a fair proportion of available water balance studies have been used to inform various models that are commonly used, e.g. grazing and crop land management, erosion, water quality and salinity risk assessment. While models must be used with caution they are most useful when used in combination with measurements and can overcome some of the limitations involved viz short term, poor sample of climate, few experimental treatments.

A further reason for lack of modelling of experimental sites is that the soils have not been characterised sufficiently to allow the models to be used at these sites. Again, in the dryland cropping & pastures, we have 'simple' but necessary measurements like soil water holding capacity, for over 150 soils (Dalgliesh & Foale 1998). This lack of this basic soils physical data limits the use of water balance models across the cotton industry. University of Sydney collected some such data and their efforts to build tools to estimate (useful) soil properties from other properties is a step in the right direction. (Ironically, this type of work started with Shaw & Yule in the EIA in the early 1970's).

This project will at least start to address these issues by capturing some data from past studies (at least the low hanging fruit), and work along side current studies to measure the critical bits for modelling.

In addition to working at the soil profile scale, we received additional funding to investigate the issue of: **deep drainage – where is it going and what is it doing?** This included funding from Condamine Alliance (Condamine groundwater and deep coring), DERM SWR (Condamine groundwater studies), QMDC (Border-Moonie drilling), Border-Gwydir CMA (Border Rivers TEM imaging).

This project is part of a set of CRC projects designed to link paddocks/fields to responses in catchments and streams:

Project 1: Measuring water balance and deep drainage in irrigated fields (CRDC & CRC, McGarry et al.) in CRC Program 1, Output 1.2

Project 2: Capturing soil water balance and deep drainage knowledge under irrigation in models across CRC Program 1, Output 1.2, Program 2 Outputs 2.2 & 2.5

Project 3: Linking deep drainage at the farm level to groundwater recharge, river flow and water quality at river basin scale. Program 2 Outputs 2.2 & 2.5

The third project has not been initiated.

3. Objectives

This project sought to:

(a) Capture data from previous and current studies of water balance and deep drainage under irrigation in N NSW and Qld in a form useful for modelling.

(b) Characterise the soil hydraulic properties (e.g. water holding capacity) of sites used for past & present water balance and deep drainage studies, so that these studies can be modelled & so we have better knowledge of relevant soil properties across the growing areas.

(c) This will include measurements in the regolith/unsaturated zone below the root zone, particularly to define the moisture status – is there a buffer or is it nearly full?

(d) Use these data to test water balance models and derive model parameters, particularly the deep drainage calculations, incorporating effects of management where possible.

(e) Use the models to enhance understanding of water balance at the experimental sites and to provide similar insights at other sites and over longer time periods, especially in CRC groundwater/catchment modelling studies.

4. Methods and Results

Progress against milestones

Table 1 Milestones to be achieved during the project (revised dates and additional 2010 extension milestones)

Date for achievement	Description of milestone or deliverable & Progress	Key Performance Indicator of Achievement & outcomes
1. 01 Mar 07	Staffing of project arranged	Staff employed
Progress	Jenny Foley, Soil Scientist employed from 01 Mar 07 0.4 FTE Brett Robinson, Modeller employed from 23 July 07 0.5 FTE	Delay in hiring Brett caused about a 6 month delay in progress in modelling
2. 01 Apr 07	Project steering committee formed including reps from NRW, CMAs, Cotton industry, collaborators (eg UTS/UNSW)	First meeting held
Progress	Advised by Graham Harris that steering committee no longer required, but have maintained contact with Graham as an informal steering committee.	Completed/on-going
3. 30 Jul 2006	3 workshops with growers, CMA & management systems providers (BMP/L&WMP/SCP) to scope water balance issues & current understanding.	Meetings in Goondiwindi, Talwood and St George, run with QMDC & Water Team.
Progress	Four ½ day workshops held in Goondiwindi, Talwood, St George and Mungindi. Attended Cotton Australia LWMP meeting, St Ruth, Dalby	Completed
4. 01 Apr 07	Data sharing agreed with data owners	Permission & conditions of use in writing
Progress	Informal agreement from: - James Moss (NRW – Gordon et al. lysimeter data Macalister sites) - Des McGarry (NRW – 8 current lysimeter sites QLD and NSW) - Janelle Montgomery (NSW PhD sites) - Jenny Foley (NRW Kingsthorpe drainage lysimeter & tensiometers) - Anthony Ringrose-Voase (CSIRO, Narrabri lysimeter & tensiometers) - Chris Carroll & David Water (EIA runoff data) - Soil PAWC data Auscot (D Richards)	Completed - Data available in database – site partly characterised - Data available as required – project still active - ditto - Data obtained & modelled - Data obtained & modelled & D Rassam modelling - Data available as required – project still active - ditto - Data available in NRW database - Data obtained & modelled (Irrigated Grains)
5. 01 May 07	Determine/negotiate requirements of model users & locations where groundwater/catchment studies will need deep drainage estimates.	Report on water balance model use and needs for cotton industry, CRC & partners
Progress	Groundwater modelling: - Goondiwindi-Talwood model (UTS MSc project, Noel Merrick)	Completed - Supplied input data & deep drainage estimates

Date for achievement	Description of milestone or deliverable & Progress	Key Performance Indicator of Achievement & outcomes
	- Cox's Creek (UTS, USyd) – agreed with W Vervoort - - Toowoomba basalts groundwater assessment 2007 (DERM & consultants) - Cotton CRC Groundwater Scoping Studies – Condamine & Border-Moonie 2007 - Hodgson and Kings Creeks GeoSciences Australia (GA) 3-D visualisation project - CSIRO MDB Sustainable Yields Project for the Condamine-Balonne 2008 - Central Condamine Sustainable Groundwater assessment team 2007-> - Cotton CRC Maules Creek project (UNSW Acworth, Kelly) - APSRU projects – several (Rodriguez, Carberry) - WaterPak for Grains (Janelle Montgomery NSW)	- PhD student progressing – data to be supplied when needed for testing modelling - Supplied deep drainage modelling estimates - Supplied figures, maps & writing - Supplied 1000's bore logs & field tour - Supplied deep drainage estimates - Input as required e.g. recharge estimation - Could provide input if required - Input into APSIM model & testing - Was not followed up.
6. Dec 07, 08, 09, 10	Consultation with CRC Science & End User Panels & Steering Committee.	Annual meeting(s).
	Silburn attend Narrabri annual science meeting 2007 Silburn, Foley & Robinson attend Narrabri annual science meeting 2008 Foley attended Narrabri annual science forum 2009	
7. Dec 07, 08, 09	Hydraulic properties of several field sites characterised	Data provided to modeller(s)
Progress	Several sites done each year. See section 7.	To Robinson, D Rassam, Jo Owens, APSRU
8. Dec 07, 08, 09	Data from field studies compiled	Data provided to modeller(s)
Progress	Data from Montgomery PhD Data from Kingsthorpe lysimeter (Foley)	To B Robinson DERM To David Rassam (CSIRO), Jo Owens (APSRU QDPI&F) Most sites awaiting progress on previous milestone
9. Dec 07, 08, 09, 10	Models tested against several field studies	Models/parameters available for spatial modelling Interim & final reports/papers
Progress	SPLASH tested for Dalby & Burdekin & compared with Howleaky? Howleaky? tested with irrigation data from Lombok (see Robinson et al. 2007b) Howleaky? model tested for Pampas cotton soil water data 2008 HYDRUS test against Kingsthorpe data progressing (D Rassam)	See list of groundwater modelling contributions Milestone 5
10. Dec07	Share outputs/insights with Water/Extension Team	Extension material/tools

Date for achievement	Description of milestone or deliverable & Progress	Key Performance Indicator of Achievement & outcomes
Progress	See Table 2 & 3. Contributing for WaterPak for Grains. Silburn & Foley contributed to G Harris Myth Busters for irrigation (accompanying PDF provided) Meeting delayed: Project to present to Water Team meeting some time in 2008	
11. 30 Jun 08	Project review & inform funders of progress	Major progress report
Progress	Review report	Completed & submitted 30 June 2008
12. 30 Jun 08	Funding arranged for 08/09	Further yr of funds from CRC, CRDC, CA &/or QMDC.
Progress	Was progressed via Paula Jones CRC	$50,000 from CA 08/09 for coring & groundwater age dating study
	222 km of TEM transects were undertaken in the Border Rivers alluvia between Goondiwindi and Mungindi in Sept/Oct 2009. The purpose was to better map alluvial thickness, and identify shallow groundwater tables. Work was carried out by a contractor (David Allen) and funded by Border-Gwydir CMA.	$60,000 from Border-Gwydir CMA for TEM imaging & coring in Border-Moonie.
Dec 09	Extension request for an additional 12 months	Extension request submitted and approved, utilizing residual unspent funds
Jan 10		Extension granted
Project Extension milestones for 2010		
Jan10	Finalise the solute-transport (SODICS) modelling of D McGarry's deep-drainage sites.	
Progress	SODICS modelling completed from the chloride mass balance at all D McGarry & T Gunawardena sites and lysimeters (6 sites x 3 lysimeters/site).	Modelling the Cl profiles with SODICS was completed and a summary report written. However, the Cl mass balance results have turned up some very strange results. The soil profiles are gaining Cl while lysimetry and water balance modelling indicate they are draining and should be loosing Cl. Unless another source of Cl is found, it is uncertain if this will ever be resolved to allow the work to be published in a journal paper.
March 10	Finalise modelling of water balances at D McGarry's and other deep drainage sites, as well as the EM-38 study site at Pampas.	Priority to extend the research findings on deep drainage modelling
Progress	Water balance modelling (HowLeaky) assisted by all available SIRMOD analysis for irrigated seasons (2 sites in 2003-04; 5 sites in 2004-05; and one in 2005-06) of McGarry/Gunawardena sites.	Results presented at Irrigation Australia conference, June 2010, published conference proceedings (accompanies this report). A journal paper on

Date for achievement	Description of milestone or deliverable & Progress	Key Performance Indicator of Achievement & outcomes
	PAWCER calculations were completed for all deep drainage sites to assist HowLeaky model development	modelling the measured water balances is planned.
July 10	Two EM38 soil moisture measurement training workshops	
Progress	Milestone undelivered due to staff shortages in 2010	One-to-one training has occurred throughout 2010, but no formal workshops.
Aug 10	Present 2 papers (EM38 and resistivity findings) at 19th World Congress of Soil Science	Innovative method developed with EM38 depth slicing and resistivity/deep coring disseminated to the broader science community.
Progress	Poster presentations and conference papers accompany this report	Two published conference papers
Aug 10	Journal paper submitted on deep drainage modelling for irrigated ag.	
Progress	Paper accepted in Australian Journal of soil Research by Gunawardena, T. A., McGarry, D., Robinson, J. B., Silburn, D. M. 'Deep drainage through Vertosols in irrigated fields measured with drainage lysimeters"	
Dec 2010	Two Journal papers submitted (with Water Research Laboratory, UNSW) on deep soil water movement & resistivity images of Condamine irrigated sites	
Progress	Deep Geoprobe coring (to 20m) undertaken in March 2010 along native veg and irrigated paddocks along resistivity transect lines. Soil chemistry from cores is being used to enhance work being done (in collaboration with Water Research Laboratory, UNSW) on deep soil water movement and application of the Revil model to quantify water storage in the regolith from resistivity data.	Draft journal paper (Greve et al.) utilizing these data accompanies this report.
Dec10	Final report to CRC and CRDC	Dec 2010

Summary of progress against project milestones:

Soil water balance modelling of irrigated cropping

The HowLeaky? soil water balance model, including the cotton sub-model developed in this project, has been through considerable development, and rigorous testing and evaluation. New capabilities for modelling irrigation application have been added and tested. Data from our/McGarry field sites and sites researched by others (Janelle Montgomery, Tracey Willis) have been formatted and analysed in the HowLeaky? model. Detailed measurements of soil water by depth were made at the Pampas lysimeter site for one season. These data were used to test the Howleaky model. We were therefore able to make good estimates of runoff and deep drainage (see Mills et al. 2008). In general, modelling of soil water balance and deep drainage is not difficult once soil parameters (e.g. water holding capacity) and irrigation inputs are know. Further simulations will examine the relationships between irrigation management and deep drainage (see Section 9).

SODICS modelling has been completed of the chloride mass balance (CMB) at all of Des McGarry's and Thusitha's sites and lysimeters (6 sites x 3 lysimeters/site). The results are being included in a journal paper currently being drafted. Unexpectedly, the results show that the soil surface three of six sites are accumulating salt in at a rate faster than inputs via irrigation water. The mechanism for the salting of the surface soil is unknown, but the source of the salt must be either deeper soil layers (by unsaturated upward flow) or rising salty water tables (by saturated upward flow).

Soil water holding capacity profiles were measured at 3 of the lysimeter sites (allowing better modelling), the variable tension lysimeter site and at 2 other cotton farms (4 soils). These included native vegetation and irrigated sites and included deep coring (to 4-6 m) to characterise the moisture capacity and status of the unsaturated zone (below the root zone). See Section 7 and 8.

Soil moisture characteristics for all six lysimeter sites have been estimated by using the PAWCER and ROSETTA pedotransfer systems. These systems use measured soil properties (e.g. particle size analysis for sand, silt, clay %) and estimate soil hydraulic properties such as drained upper limit, lower limit and total porosity. PAWCER is giving superior results to ROSETTA, which reflects the fact that the PAWCER database included similar soil types (i.e. heavy clays). Although the ROSETTA database is much larger, it contains few heavy clay soils, and those are mainly from North America and Europe.

Mark Silburn and Jenny Foley helped Graham Harris write deep drainage 'mythbusters' article for Cottongrower.

Changes to project direction

Two other issues are apparent. Firstly, activities have come up, such as the **groundwater model** for the McIntyre-Weir Rivers area, 2008 Border-Moonie **drilling program** (funded by DERM and QMDC), **resistivity imaging** (funded by CA) and Border-Moonie **TEM imaging and coring** (funded BG-CMA) which were seen to be highly relevant and important issues for the cotton/irrigation industry. However, there are no milestones that these activities can be reported against. Note that a project proposal for this type of project was submitted to the CRC in 2006. See Sections 5 & 6.

Secondly, in the early stages of the CRC, it appeared that more catchment and groundwater system based projects were going to occur. This project was designed to provide soil water balance inputs into such projects. However, few such projects eventuated. Thus we have tended to provide input into non-CRC, often DERM, groundwater projects.

Geophysical surveying as a tool for assessing the state of water in the regolith
A number of new and fruitful research methods for measuring water in the landscape evolved during the first 3 years of this project, which we then focused on in more detail during the extension phase (2010). These include –

1. **EM38** used for monitoring and measuring soil water – Through the CRC summer scholarship program (and in collaboration with USQ and Condamine Alliance) we developed a very promising method of monitoring the soil water during cropping using an EM38 (and depth slicing the readings) to determine soil water at a range of depths. The EM38 provided soil moisture estimates for various soil layers with better accuracy and less time taken than other soil water monitoring methods. This method is non invasive, non destructive and measures can be taken in wet paddocks as vehicle access is not required. The approach is potentially attractive to industry consultants and thus useful to growers, possibly for irrigation scheduling.

2. **Resistivity imaging** to assess long term soil water changes in the regolith – We completed 2-D resistivity imaging (in collaboration with UNSW) across several transects in irrigated Vertosols of the Condamine, with very promising results that provide key information about long term trends in soil water storage and usage in the deeper regolith under natural vegetation and irrigated paddocks. We have also used resistivity imaging in shallow detailed studies to compare direct measurement of soil conductivity with measurement of apparent resistivity from EM38's and soil chemistry. Results for this work are in the accompanying draft journal paper (Greve et al.). This body of work has been recognised by Cotton CRC, with our team receiving the 'Chief Scientist Achiever Award for August 2009'. This approach is now being used in the Lockyer valley with CSIRO.

We are currently working in collaboration with Bryce Kelly and Anna Greve (Water Research Laboratory, UNSW) to improve parameterisation of the Revil model for heavy clay soils, so that resistivity imaging can be used with more confidence to estimate the amount of water to deep in the soil regolith. A series of deep geoprobe cores (20 m) have been taken in both the Condamine and Lockyer Valley on irrigated cropping lands and in native vegetation, along with accompanying resistivity imaging and full profile chemistry. This body of work, initiated through this project and continuing beyond, will address and potentially attain key knowledge and tools in the field of hydro geophysical surveying.

Where has deep drainage gone
Considerable **deep coring** using a soil sampling rig (to 6 m in unsaturated zone) occurred at a range of irrigated sites in the Condamine (Dalby, Pampas, Condamine-Bell, Talwood, Brookstead) to track "where has the deep drainage gone too?" A major finding of the project was that the upper unsaturated zone (between below the root zone to 4-6 m) is filled to near saturation under all irrigated sites; and remains very dry under all native

vegetation sites. This finding was confirmed and verified with the geophysical surveying (see section 7).

This zone of near-saturated 'filled' profile under irrigation potentially extends beyond 4-6 m cored with the soil coring rig.

Border-Moonie drilling program

The Border-Moonie was recognised to have potential future salinity risks (Biggs et al. 2005), particularly on the Border-Weir Rivers alluvia where irrigation occurs. While no larger project was funded to investigate these issues, **a multi-point plan** was prepared (Section 6; Table 4) and small amounts of funding obtained to implement this plan step-by-step over time. This included:

- Preliminary **groundwater modelling** of part of the Macintyre alluvia. See Section 5.
- A **drilling program** in the Border-Moonie in 2008-09 was completed, where some 35 holes (all fully described & sampled for chemistry) were drilled and 31 monitoring bores constructed with several nested bores. Bores were drilled in lines across the landscape approx. at right-angle to the streams, providing a systematic groundwater monitoring network for the region, linking up with monitoring bore lines in NSW. Water level loggers were installed in bores near irrigated fields. Water in bores was sampled for ionic chemistry and EC. This was funded by QMDC and DERM, with staff input from the project. See Section 6.
- In 2010-09, a **TEM imaging survey** was conducted using a mobile ground survey across 100's km in the Border-Moonie. This provided depth sliced conductivity images to below 30m in lines across the landscape, similar to resistivity imaging. Some features in these images were investigated using rotary core drilling. The cores were sampled for soil moisture and chemistry. Some holes were constructed as monitoring bores. This was funded by BG-CMA and DERM, with staff input from the project.
- Andrew Biggs, DERM Toowoomba, led these latter two parts of the project.

Progress against specific deliverables for QMDC and Condamine Alliance

QMDC:

- Water cycle pathways for major irrigated soils documented.
  - Water cycle pathways (runoff, deep drainage, transpiration, soil evaporation) are defined:
    (a) in the outputs of modelling studies, such as those done for the Irrigated Grains project (Sections 9) and the Summer Scholarship EM38 study (see Mills *et al.* 2008), and
    (b) in experimental studies such as the drainage lysimeter study at Kingsthorpe (Section 8) – while not in the QMDC area, this study helps us to ensure that the models we use are working well.
  - Deep drainage estimates were provided to David Whiting for the McIntyre-Weir river groundwater model (see Section 5) and to the CSIRO MDB Sustainable Yields Project for the Condamine-Balonne.
- Two extension events (type to be agreed), involving QMDC technical staff and key community members. The purpose of the events will be to help technical staff incorporate information collated through the project into their extension messages/materials.
  - Four half-day workshops were held in Goondiwindi, Talwood, St George and Mungindi with cotton growers and the local Regional Body (QMDC) and government staff, organised locally by Emma Carrigan (DPI&F), Veronica Chapman (DPI&F) and Rebecca Smith (IAWM). Mark Silburn, Andrew Biggs and Des McGarry (or Thusitha Gunawardena) and Lauren Eyre (QMDC) presented on water balance, groundwater and salinity knowledge or lack there of. One outcome of this is was the funding for the regional groundwater monitoring network installed in the Border Rivers-Moonie in 2008, in collaboration with QMDC sub-catchment groups and IAWM.
  - Two field days were run at Talwood and Nindigully by Andrew Biggs and Kristie Watling (DERM) during the 2008 drilling program to inform local landholder about the program.
  - Presentations were made about deep drainage and groundwater at the QMDC Annual Meeting and NRW Regional Science Forum.
- Fact sheets, or similar tools, which capture the learning from the project. These materials will build on the work that has been completed through the WaterPak paper.
  - These will be prepared as the learnings from the project become clear. We are very interested in preparing a fact sheet on the issue of over irrigating and why no measured change in subsoil water contents (e.g. in C-probe reading) does not mean the water is not infiltrating and irrigation must continue. This is a common misconception. We can provide simple instructions for diagnosing this problem using tensiometers – a service that could be provided by consultants.
- All project progress reports, provided by DERM, are forwarded to QMDC over the life of the project.
  - This is done through the CRC Centric website and CRC reporting process. In addition, brief reports are prepared upon request from the Regional Bodies.

Condamine Alliance:

- Provision of a deliberate link from science outcomes of the project to extension of the findings
  - The best way we can ensure the outcomes from the project are used in extension is to work through the existing Cotton Water Team and Extension Team and to provide input into tools such as WaterPak and WaterPak for Grains (see Section 9).
  - We also provide results from field sites directly back to the grower and their farm team and advisors.
- Links from project outcomes to adoption of change practices consistent with the BMP
  - The project is contributing water balance estimates for various management options for the WaterPak for Irrigated Grains project with Janelle Montgomery.
  - Project staff are involved in the Central Condamine Sustainable Groundwater Management team with DERM Water Services, which will progressively develop and implement sustainable management of groundwater in all major aquifer systems in the Condamine.
  - Project staff did the deep drainage/recharge estimation for the Toowoomba basalts groundwater study 2007 (see Publication 7).
  - Deep drainage estimates were also provided to the CSIRO MDB Sustainable Yields Project 2008 for the Condamine-Balonne.
- Link with other CA funded projects in partnership with Cotton Catchment Communities CRC.
  - The project works closely with Project 1.02.04 (Des McGarry). We are progressively measuring important soil properties at each of Des's sites (Section 7). We also collaborate and share techniques on groundwater monitoring – Des looks after St. George Irrigation Area monitoring while we monitor groundwater in the Border-Moonie and Condamine.
  - Condamine Alliance is funding DERM/Project 2.01.02 in 2008/09 to conduct a study in the Central Condamine Alluvial groundwater system, (a) a coring study to trace deep drainage water in the unsaturated zone to determine how far the water has moved down and see if it is connecting to groundwater, and (b) ionic chemistry and isotope measurements in groundwater to determine the age of the water and to trace the sources of the water (e.g. from rainfall, river or from surrounding rocks).
  - Project 2.01.02 provide borehole logs and stratigraphy data from some 1000's of bores in Hodgson and Kings Creeks catchments to GeoSciences Australia (GA) for the 3-D visualisation project and a field tour for GA staff.
- Two (2) key sites to be located in the Condamine catchment
  - Three key sites are located in the Condamine – near Dalby, near Pampas (see Section 7) and Kingsthorpe Research Station (Section 8).
- All project progress reports, provided by DERM, are forwarded to CA over the life of the project.
  - This is done through the CRC Centric website and CRC reporting process. In addition, brief reports are prepared upon request from the Regional Bodies.

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

Publications in preparation

1. Foley JL, Silburn DM, Pegler D, de Voil R, Huth NI, Drever I (in prep.) Measurement of deep drainage in a swelling clay soil using a variable tension lysimeter. I. Fallow drainage and water balance under natural rain.
2. Foley JL, Silburn DM et al. (in prep.) Measurement of deep drainage in a swelling clay soil using a variable tension lysimeter. II. Under flood irrigation.
3. Gunawardena, T. A., McGarry, D., Robinson, J. B., Silburn, D. M. Deep drainage through Vertosols in irrigated fields measured with drainage lysimeters, *Australian Journal of Soil Research* (accepted)
4. Greve, A., Kelly, B., Foley, J. L., Silburn, D. M. Electrical resistivity to quantify soil moisture variations in clay soils in the field—which accuracy is realistic? (Draft for Vadose Zone Journal)

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Presentations and public relations

Half-day workshops were held in Goondiwindi, Talwood, St George and Mungindi with cotton growers and the local Regional Body (QMDC) and government staff, organised locally by Emma Carrigan (DPI&F), Veronica Chapman (DPI&F) and Rebecca Smith (IAWM). Mark Silburn, Andrew Biggs and Des McGarry (or Thusitha Gunawardena) and Lauren Eyre presented on water balance, groundwater and salinity knowledge or lack there of. One outcome of this is was the funding for the regional groundwater monitoring network installed in the Border Rivers-Moonie in 2008, in collaboration with QMDC sub-catchment groups and IAWM. Several growers also opted to pay for monitoring bore as they are useful for Land and Water Management Plans and BMP.

Table 2 Extension activities during the project

Date	Group	Title of Workshop	No. of Participants	No. of Males /Females	Average Client Satisfaction Rating (1-5)*
July 06	Cotton BMP & LWMP, St Ruth hall, Dalby	Land & Water Management Plans	About 15		
11th July 06	Goondiwindi Irrigators, NRW, DPI&F and QMDC	Where does the water go?	25 people (5 growers 2 consultant)	15:10	3
11th July 2006	Talwood Irrigators, NRW, DPI&F and QMDC	Where does the water go?	11 people (4 growers)	7:4	4
12th July 2006	St George Irrigators, NRW, DPI&F and QMDC	Where does the water go?	About 15		
6th Nov 2006	Mungindi IAWM Group, NRW and QMDC	Where does the water go?	About 30		
29th Mar 2007	NRW, CA, QMDC	Progress meeting DERM Cotton CC CRC projects			
April 2008	Talwood grower field meeting Nindigully landholders field meeting	Border-Moonie groundwater investigation drilling program			

Results from the EM38 study were presented to CSIRO, DPI&F and DERM staff at an Irrigated Farming Systems meeting on 13th May 2008. Detailed method/results descriptions have also been presented to Fernanda Dreccer (CSIRO Plant Industry, Gatton), Greg McLean (Agricultural Systems Modelling, DPI&F, Toowoomba) and Jochen Erberhard and Jack McHugh (NCEA USQ, Toowoomba) for implementation in their research.

Table 3 Communication event where project leader or staff presented.

COMMUNICATION EVENTS

S – scientific meeting, M – media, G/C – grower/advisor/community, Gov – Government, RB – NAP Regional Bodies

Date	Type	Event	Audience	Where
2010				
Dec-10	Meeting	J Foley presented: "Our Toolkit" Geophysical surveying, EM38 soil water monitoring, Groundwater monitoring, Shallow soil coring–deep coring - to measure and monitor movement of water and salts to deep in regolith/groundwater	S/Cotton CRC/Gov	Armidale
Sept-10	Conference	M Silburn, Melanie Shaw & Craig Thornton. "Pesticide runoff under rainfall and furrow irrigation" Presentation: "Water quality and the Great Barrier Reef" Symposium. "Challenges in Environmental Science & Engineering", CESE-2010, 26th Sept- 1st Oct 2010, The SEBEL, Cairns, QLD.	Sci/rural ind	Cairns
Aug-10	Conference	Gunawardena, T. A., McGarry, D., Gardner, T. Will increased water use efficiency lead to salt accumulation in the root zone? A comparison of adjacent lateral move and furrow irrigation systems	Cotton/Sci/Rural ind	Gold Coast
Aug-10	Conference	Des McGarry, Thusitha Gunawardena, Jenny Foley. Controlling deep drainage for improved WUE - and possible links with ground water movement; 2010 Australian Cotton Conference	Cotton/Sci/Rural ind	Gold Coast
Aug-10	Conference	Foley JL, Silburn DM, Greve A (2010) Resistivity imaging across native vegetation and irrigated Vertosols of the Condamine catchment—a snapshot of changing regolith water storage. In '19th World Congress of Soil Science'. Brisbane, Queensland. pp. 159-162	Sci	Brisbane
Aug-10	Conference	Robinson JB, Silburn DM, Foley JL, Orange D (2010) Root zone soil moisture content in a Vertosol is accurately and conveniently measured by electromagnetic induction measurements with an EM38. In '19th World Congress of Soil Science'. Brisbane, Queensland. pp. 78-81	Sci	Brisbane
Jul-10	Field tour	Silburn, Foley, Harris: Filed presentation for 19th World Congress of Soil Science pre congress tour	Sci	Pampas
Jul-10	Conference	Mark Silburn, Bronwyn Masters, Ken Rohde. "Management of pesticide runoff in Great Barrier Reef catchments: lessons from cotton and cane", World Pesticidxes Congress, IUPAC Melbourne	Sci	Melbourne
Jun-10	Conference	Thusitha Gunawardena, Des McGarry and Ted Gardner: Australian Irrigation Conference	Sci/rural ind	Sydney

		and Exhibition 2010: Will increased water use efficiency lead to salt accumulation in the root zone? A comparison of adjacent lateral move and furrow irrigation systems		
Mar-10	Training	J Foley attended two day Geophysical Training workshop with Water Research Laboratory, UNSW, Sydney	Sci	Sydney
Feb-10	Workshop	Brett Robinson – training modelling water balance		
2009				
Dec-09	Invited lecture	M Silburn presented "Groundwater geochemistry, & resistivity imaging Central Condamine, Qld" for Condamine Catchment Management Assoc. & Australian Centre for Sustainable Catchments, University of Southern Queensland	Sci/rural ind	Toowoomba
Aug-09	Science forum	J Foley presented "Resistivity imaging, EM38 and soil coring measurements of water in irrigated Vertosols of the Condamine catchment" at Cotton CRC Science Forum	Sci/rural ind	Narrabri
Aug-09	Conference	M Silburn presented: "What drives pesticide runoff: An empirical journey to a framework for pesticide runoff using some of Don Wauchope's ideas" for CRDC & L&WA Travel Fellowship American Chemical Society, 238th National Meeting.	Sci	Washington DC, USA
Aug-09	Science day	M Silburn presented "Science and Groundwater in the Condamine" / demonstration by J Foley & R deVoil at National Science week presentation	Sci/DERM	Toowoomba
May-09	Workshop	M Silburn presented "Deep drainage & groundwater in Queensland" at Cotton Catchment Communities CRC/ACRI research forum on deep drainage in irrigated cotton farming systems.	Cotton CRC/Sci	Narrabri
May-09	Workshop	J Foley presented "Water balance changes under irrigation in the Condamine …and measuring soil water under irrigated cotton using an EM38" at Cotton Catchment Communities CRC/ACRI research forum on deep drainage in irrigated cotton farming systems.	Cotton CRC/Sci	Narrabri
May-09	Workshop	Participation and presentation of simulation modelling results at the Cotton Catchment Communities CRC/ACRI research forum on deep drainage in irrigated cotton farming systems.	Cotton CRC/Sci	Narrabri
May-09	Training	'B Robinson ran Soil Water Balance & Irrigation Modelling (Howleaky) training (~8 attended)	Sci	Mackay

May-09	Training	'B Robinson ran Soil Water Balance & Irrigation Modelling (Howleaky) training (~8 attended) A total of 11 public sector researchers and 2 private consultants are now skilled in using the model. This includes 4 scientists involved in cotton and deep drainage modelling (JF, PT, TG and BR)	Sci	Toowoomba
May-09	Workshop	Minimising off-site movement of pesticides and nutrients (L&WA). M Silburn presented "Management of water quality from crop lands - Cotton BMP experiences	Sci/Rural ind/NRM	Cairns
Apr-09	Training	'CRC-IF Solutes master (deep drainage methods) class attended by M Silburn	Sci	Adelaide
Apr-09	Lecture	M Silburn presented "Salinity in Queensland – hydrologic change from soils to catchments" at Flinders Uni, Adelaide, staff and graduate students	Staff and graduate students	Adelaide
Jan-09	Award	M Silburn was presented with an NRW Australia Day 2009 Achievement Medallion by the Minister	Gov	Brisbane
2008				
Dec-08	Meeting/seminar	J. Foley-Presentation of our project results on DD under irrigation to scientists with 'Increasing the resilience of Eastern Australian irrigated farm (new project)'	Sci/Gov	Toowoomba
Nov-08	communications	A collection of information concerning contemporary methods of participatory action research, and insights into current R, D and E styles and methods was sent to Dr Paula Jones of the CCC CRC.		
Nov-08	Seminar	J. Foley -Water Taps USQ - "Measuring soil water under irrigation using an EM38"	Sci/Gov/G/C	Toowoomba, USQ
Nov-08	Forum	J Foley- Discussion forum of 'Irrigators' decision-making: an exploratory study', USQ	Sci/Gov	Toowoomba, USQ
Oct-08	Seminar	M. Silburn-ASSSI Lecture -Hydrologic change from soils to catchments salinity & groundwater supply	Sci/C	Brisbane, UQ
Oct-08	Forum	M Silburn-CCC- CRC Annual Science Forum Oct 08- Deep drainage: how much, when and where? Or 10 years in 15 minutes	Sci/Gov/G/C	Narrabri
Jun-08	Seminar	M. Silburn presented at Felton Valley Landholders meeting - The science of the invisible- where does groundwater come from and what does it get up to?	Community	Felton
May-08	meeting	Irrigation modelling meeting w. CSIRO, DPI&F, NRW	Sci/Gov	Toowoomba
Apr-08	field day	Drilling investigation field day - Nindigully (Biggs, Watling)	G/C	Nindigully

Apr-08	field day	Drilling investigation field day - Talwood (Biggs, Watling)	G/C	Talwood
31 Mar-3 Apr 08	Conference	2nd International Salinity Forum - 5 papers and presentations (Silburn , Biggs)	Sci	Adelaide
3-Mar-08	meeting	Condamine Alliance - planning groundwater isotope & coring studies	Sci/Gov	Toowoomba
18-21 Feb 08	Workshop	ewater CRC annual science meeting (Silburn - surface-groundwater interaction project)	Sci/Gov	Gold Coast
15-Feb-08	meeting	NRSc recharge estimation SPLASH meeting	Gov	Indooroopilly
8-Feb-08	meeting	Science meeting NRW, CA, QMDC	Gov, RB	Toowoomba
2007				
29-Nov-07	Conference	Presentation to NRW Regional Science Forum (Silburn "The science of the invisible - groundwater, where does it come from and what is it up to?"	Sci/Gov	Toowoomba
16-Nov-07	meeting	Condamine Groundwater Management Area meeting, Mineral House	Gov	Brisbane
4-Oct-07	meeting	Presentation to QMDC annual meeting (Silburn "Groundwater and salinity")	RB, Gov	Toowoomba
17-18 Oct -07	Conference	Presentation to NRW Water Monitoring Conference (Silburn "Uses of groundwater data")	Sci/Gov	Brisbane
22-23 Aug-07	Workshop	Sustainable management of groundwater in Central Condamine (Silburn)	Gov	Bunya Mts
6-9-Aug-07	Conference	Cotton CC CRC Annual Science Meeting (Silburn "Overview of Project")	Sci	Narrabri
27-Jul-07	meeting	Meeting with Water Planning on New Science in SPLASH recharge estimation & irrigation demand modelling (Silburn & Robinson)	Gov	Indooroopilly
18-May-07	meeting	Presentation to NRW Science Panel (M Silburn)	Gov	Toowoomba
23-24 Apr 07	meeting	Salinity SIP annual team meeting (M. Silburn, P. Tolmie)	Gov, RB	Malany
19-Apr-07	meeting	Planning Border-Moonie drilling program (M. Silburn & QMDC)	RB	Toowoomba
29-Mar-07	meeting	Participants in meeting with QMDC and Condamine Alliance – groundwater and salinity monitoring (M. Silburn)	RB, Gov	Toowoomba
27-Mar-07	meeting	MDBC Basin Salinity Management Strategy meeting (M. Silburn)	Gov	Canberra
2006				
13-15 Dec 06	conference	Paper on salinity & groundwater in Hodgson Creek, Hydrogeology/Isotopes Conference (Silburn, Cresswell)	Sci	Adelaide
05-Dec-06	meeting	Presentation to Maranoa-Balonne Catchment Management Association 'Tools and skills for	G/C, Gov, RB	Miles

		managing salinity risks (and salinity)' (B. Robinson)		
29-Nov-06	workshop	Condamine Alliance Catchment Scorecard Workshop (M. Silburn)	RB	Toowoomba
27-Nov-06	seminar	APSRU seminar 'HowLeaky? – An instructive model for exploring the impact of different land uses on water balance and water quality' (B. Robinson, D. Rattray)	S/Gov	Toowoomba
06-Nov-06	workshop	Workshops to brief irrigators, NRM & Regional Bodies staff on groundwater, salinity & water balance issues in Border Rivers-Moonie, Balonne (Silburn, McGarry), QMDC, IAWM and Irrigation Ag-SIP (Carrigan, Chapman etc)	G/C, RB, Gov	Mungindi
09-Nov-06	review	MDBC Integrated Audit Group (IAG), presentation on 'Overview of progress in modelling salinity in QMDB' (M. Silburn	Gov, S	Brisbane
25-26 Sep 06	conference	CGS Groundwater School, presentation on 'Recharge-discharge' (M. Silburn)	S/Gov, RB	Brisbane
18-20 Sep 06	**conference**	MDB Groundwater Workshop (M. Silburn, A. Biggs) **- 4 papers & presentations**	S/Gov	Canberra
12-13 Sep 06	meeting	Qld salinity team meeting (Silburn, Owens, Robinson, Tolmie, Rattray, Cresswell etc)	S/Gov	Brisbane
29-Aug-06	meeting	Meeting with Condamine Alliance, QMDC, SW-NRM and NRMW staff to plan the BRS Community Monitoring of Salinity across the three regions (M. Silburn)	RB/Gov	Toowoomba
22-23 Aug-06	workshop	Fitzroy Salinity Risk Framework workshop (M. Silburn, J. Owens)	S/Gov, RB	Brisbane
11-12 July 06	workshop	Workshops to brief irrigators, NRM staff & Regional Bodies staff on groundwater, salinity & water balance issues in Border Rivers-Moonie, Balonne (Silburn, Biggs et al.,) and Irrigation Ag-SIP (Carrigan etc)	G/C, RB, Gov	Goondiwindi
11-12 July 07	workshop	Workshops to brief irrigators, NRM staff & Regional Bodies staff on groundwater, salinity & water balance issues in Border Rivers-Moonie, Balonne (Silburn, Biggs et al.,) and Irrigation Ag-SIP (Carrigan etc)	G/C, RB, Gov	Talwood
11-12 July 08	workshop	Workshops to brief irrigators, NRM staff & Regional Bodies staff on groundwater, salinity & water balance issues in Border Rivers-Moonie, Balonne (Silburn, Biggs et al.,) and Irrigation Ag-SIP (Carrigan etc)	G/C, RB, Gov	St George
15-Jun-06	meeting	Meeting with Condamine Alliance, QMDC, SW-NRM and NRMW staff to plan the BRS Community Monitoring of Salinity across the three regions (M. Silburn)	RB/Gov	Toowoomba
08-Jun-06	workshop	Cotton Australia land & water management planning/BMP workshop (M. Silburn)	growers	St Ruth Hall (near Dalby)

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5. Groundwater model of McIntyre-Weir River (Goondiwindi to Talwood)

This work was undertaken as a Masters of Science project at University of Technology, Sydney (UTS), by David Whiting. The project was supervised by Prof. Noel Merrick, Dr. Bryce Kelly (both then UTS) and Mark Silburn (DERM), members of the Catchment Program in the Cotton Catchments Communities CRC. Project 2.01.02 provided deep drainage estimates for combinations of land use, soils and climate in the study area, which were used in the model.

Numerical groundwater modelling (MSc Thesis)

The study resulted in a Thesis and a numerical groundwater model (held y UTS). The citation for the thesis and the abstract are reproduced below.

Whiting D (2007) Groundwater modelling study – Border Rivers Floodplain, Queensland. Unpublished MSc Thesis, University of Technology, Sydney.

ABSTRACT
Recent investigations of the Border Rivers region have indicated rising groundwater levels in crop irrigated areas and widespread high groundwater salinities. A preliminary groundwater salinity assessment was undertaken in a region subjected to crop irrigation on floodplain alluvium between Weir, Macintyre and Barwon Rivers in Queensland. A single layered numerical groundwater model of the floodplain alluvium was developed to identify areas susceptible to groundwater emergence and salinisation.

The hydrogeological assessment of the region indicated that floodplain alluvium is generally 20 to 30m thick and spatially highly variable in lithologies varying from clay to coarse sand/gravel layers. Groundwater levels are sympathetic to topography and indicate an unconfined system. A steady state groundwater model was developed. The model was calibrated against groundwater heads with groundwater contours interpolated from measured groundwater levels across the region providing a hydraulic conductivity range of 5 to 50 m/d for the saturated alluvium. A series of transient state scenarios were simulated applying specific yields of 0.15 to 0.30, hydraulic conductivity values of 5m/d and 50m/d and surface recharge rates 0.1, 1 and 10 times the deep drainage rates for different soil and land use types derived from soil water balance modelling results from Department of Natural Resources and Water (NRW).

Results indicated near surface groundwater mounding and surface groundwater emergence was characterised in areas with a combination of a) crop irrigation and b) shallow depth from surface to starting groundwater heads. These areas were generally in the south to south-western part of the project area near Barwon River where starting groundwater heads were shallower. Shallow groundwater mounding and surface emergence was most sensitive to hydraulic conductivity and surface recharge rate applications.

The assessment highlighted deficiencies in available spatial and temporal groundwater data, topographical elevation data and hydrogeological data produced major uncertainties in characterising the groundwater regime for the region and modelling resolution. There was insufficient spatial and temporal groundwater salinity data to discriminate vertical or horizontal salinity zoning.

Recommendations for further work to improve resolution of modelling groundwater salinisation outbreak in the region include a) targeting field drilling and groundwater monitoring in areas identified through this modelling as susceptible to shallow groundwater mounding and surface outbreak; b) improve hydrogeological conceptual model of region by conducting drilling investigations to characterise layering within the alluvium and hydraulic interaction between underlying Griman Creek Formation and the alluvium; c) conducting more detailed elevation survey surveys, particularly along the major rivers reaches; d) groundwater investigations to asses river interaction with groundwater system; e) improve groundwater spatial and temporal data resolution across the region by installing more observation bores and monitoring more frequently; f) introduce more paired control and irrigated monitoring groundwater stations; and g) characterise saturated alluvium hydraulic properties by conducting single borehole testing or pumping tests on established bores or strategically placed bore sites.

Outcomes and further investigations

David identified a large number of limitations to the resolution and inputs of the groundwater model. DERM in collaboration with QMDC and this Project have been working the overcome these limitations – the required activities and their status are described in the following table (Table 4).

Table 4 How to address the groundwater and salinity issues in Border-Moonie region

To determine the risks of salinity in the Border-Weir alluvia, and the eventual needs for management require improved knowledge of the following:

Task, tools or process	Purpose (what we get from it)	What is needed	Status
Consultation with landholders, QMDC & industry	Inform about what we do & don't know & begin engagement	Landholder to understand the risks/treats, undertake monitoring, use LWMP process to plan improved water management.	Four ½ days workshops held in Goondiwindi, Talwood, St George & Mungindi Two field days held during 2008 drilling program (Talwood and Nindigully)
Drilling program (hydrogeological investigation)	a) Regional groundwater monitoring network b) Regional scale hydrogeological conceptual model (cross-sections & long section plots of aquifers etc) c) Improve knowledge of extent of saline/acid groundwaters	Drill & construct monitoring bores in lines across the valley, with sites specifically in dryland farming and irrigated areas. Include multiple aquifer depths at selected sites. Down hole EM & gamma EC & Cl profiles on drill chips	Funding from QMDC & DERM in 07/08, carried out in 2008-09 by Andrew Biggs and Mannion Drilling. Some 35 holes were drilled and sampled and 31 monitoring bores were constructed in 2008. Further bores were drilled, samples and constructed in 2010 by rotary core drilling.
Surveying	Define the elevation of land, groundwater surface & stream beds	Survey in monitoring bores. Survey land surface along bore transects & river cross-sections – check new 5m DEM	Initial agreement with DERM Surveyors 5m DEM constructed by DERM
Geophysics	Understanding aquifers/materials between drill holes.		
TEM	Regional level depth sliced image of EC & inferred material properties (aquifers, salinity, clay, sand etc) along transects across valley.	Land/boat based survey of transects with TEM Depth sliced image of EC & inferred properties.	Proposals submitted to CCC-CRC & CRDC (not funded) & NPSI Jan 2008 (not funded) with UTS (Allen/Merrick). Funded by BG-CMA 2009 and land based TEM survey conducted by David Allen.
Resistivity imaging	2-D images of material properties (e.g. conductivity/wetness) of unsaturated/saturated zones	Paddock level transects through irrigated fields, channels/dams, dryland cropping, pasture/native veg. Eg few 100's m long. Coordinate with unsaturated zone moisture coring (below).	Proposals submitted to CCC-CRC & CRDC (not funded) with UNSW (Acworth/Timms/Kelly). DERM now capable of this work.

Task, tools or process	Purpose (what we get from it)	What is needed	Status
Stream monitoring & rapid stream survey (RSS)	a) Stream flow-EC/salt load relationships & salt loads, as benchmark for comparison with future – is salinity increasing? b) Locate any sites where saline groundwater is discharging to streams	a) Data for improved stream flow-EC/salt load relationships (EC through full flow range) & calculated salt loads. b) RSS to find sites where saline groundwater is discharging to streams	BFF commissioned to monitor Jan-Jun 08, funded by DERM SWR. Results not as comprehensive as planned.
Groundwater monitoring	Water level surface & change over time	Scaled monitoring – loggers in bores near irrigation or streams, monthly then quarterly near dryland cropping, quarterly then annual in native vegetation.	Four loggers in place 2007. BFF commissioned to monitor Jan-Jun 08, funded by DERM SWR.
Land Resource Survey	Improved soil mapping for use in salinity assessment, deep drainage estimation, soil salt loads, LWMP's.	Improved, seamless coverage of soils (boundaries & characteristics) for deep drainage mapping, salt load calculation, LWMP's.	Proposals submitted to NPSI Jan 2008 (not funded).
Monitor rainfall	Improve network of rainfall stations	Consult landholder regarding their stations & obtain data sharing agreements/data, install pluviometers near bores with loggers.	No action yet.
Monitor irrigation	Know which fields irrigated in which years.	Need a record of where water is applied for historical/future.	BFF commissioned to monitor Jan-Jun 08, funded by DERM SWR – not carried out.
Deep drainage estimation	Spatial estimated of historical deep drainage for combinations of landuse/soils/climate.	a) Better physical characteristics of soil (e.g. PAWC), & better soil mapping (above) b) test models vs measured drainage (McGarry et al data) c) estimate deep drainage for landuse/soil/climate combinations for input to groundwater modelling.	Cotton CC CRC Project 2.01.02 (Silburn), co-funded by QMDC & CA measuring PAWC & to test modelling at some sites in target region. Soil hydraulic properties collected for 3 soils in alluvia of different ages.

Task, tools or process	Purpose (what we get from it)	What is needed	Status
Unsaturated zone moisture status/lag time	Define time-lag of deep drainage to travel though the unsaturated zone – how long before it becomes groundwater recharge? Is fresh (deep drainage) water perching on saline (groundwater) water?	Coring in unsaturated zone in irrigated, dryland and native vegetation sites, measurement of moisture content & potential, bulk density, EC & Cl. Pore fluids also useful. Isotope tracer studied also useful.	Two site cored by Cotton CC CRC Project 2.01.02 (Silburn) in Condamine alluvia and 2 in McIntyre alluvia. 5 more done with rotary coring in 2010 (Biggs & Mannion).
Water use by deep rooted vegetation.	How much saline groundwater do native trees use in the alluvia? This is a potential source of diffuse groundwater discharge.	Combination of isotope & sapflow measurements will define tree water use & source of the water.	ARC Linkage Grant application (Biggs) 2008 submitted with UQ (not funded).
Pump tests on bores	Define storativity & hydraulic conductivity of aquifer materials (S & K).	Pump/slug tests on bores, preferably using multiple observation holes around pumped hole.	No plan as yet.
Groundwater chemistry	Ionic chemistry and isotopes can be used to trace the sources of the water and determine the age of the water.	Purge bores and pump samples for water chemistry.	Ionic chemistry measured during 2008/09 (Salinity budget) and 2010 (BG-CMA).
Groundwater modelling	Determine time course & locations of groundwater rise relative to land surface and stream beds.	Numerical (eg MODFLOW) model of groundwater system with river discharge. Uses all data outlined above.	Preliminary model build by MSc student (David Whiting) UTS, mainly exposing many data limitations.

6. Investigation of stratigraphy and groundwater in the Border-Moonie areas

The starting point for implementing the plan outlined above (Table 4) was to undertake the drilling program, to better define the geological stratigraphy and to create a regional groundwater monitoring network.

Background

The western Macintyre and Weir River alluvia are located in the Border Rivers catchment, between Goondiwindi and Mungindi, in southern inland Queensland and in northern inland NSW (Figure 1). The Border-Moonie Salinity Audit (Biggs *et al*. 2005) identified this area as having the highest risk of salinity affecting valuable assets in the region. This was due to the relatively shallow groundwater levels, the extreme salinity of groundwater, large irrigation development (with evidence of rising groundwater levels), low slopes, permeable red soils in the upper landscape, and the intensity of development close to streams. Groundwater in the alluvia is highly saline (EC 30,000-60,000µS/cm) (Figure 1) and sometimes acid (e.g. pH=4). Acid sulphate soils have recently been found.

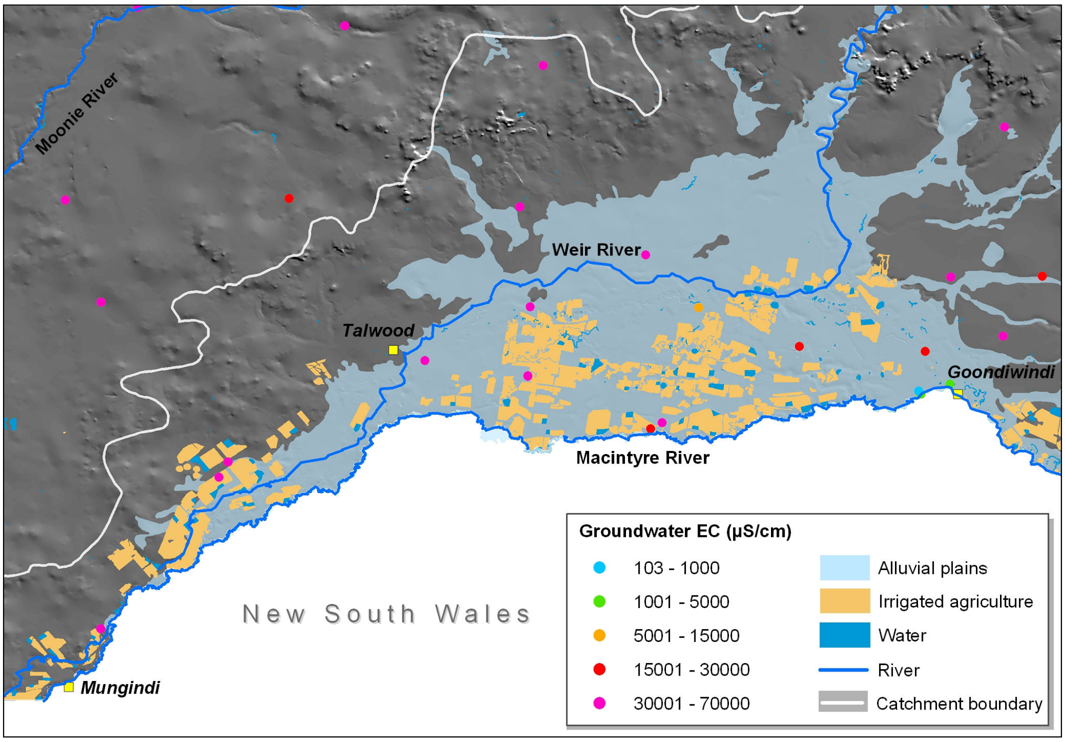

Figure 1. Western Macintyre (Barwon) and Weir River alluvia between Goondiwindi and Mungindi, in the Border Rivers, Qld, and groundwater salinity.

There are two threats:

1) groundwater rise due to irrigation deep drainage and leakage from channels & storages, causing discharge of saline groundwater & acidity to the streams and land salinity,

2) groundwater rise in the dryland cropping lands north of the alluvia (similar to Goondoola salinity outbreak) due to deep drainage, with related local salinity outbreaks, and groundwater flow into the alluvia, exacerbating the former issues.

There are significant assets at risk: good quality irrigated land (70,000 ha), irrigation infrastructure (or development costs), good quality stream flows in the rivers. There were few groundwater monitoring bores in the area (Figure 2).

2007/2008 drilling program

During 2007, a drilling program was planned to improve knowledge of groundwater and stratigraphy in the Border-Moonie (Figure 2), with funding from QMDC and DERM, and input from Project 2.01.02. This included a series of four ½ day meetings and presentations to brief landholders and regional Government and QMDC staff on the potential issues and the purpose of the drilling program. Two irrigators also provide funding for bores on their properties. New monitoring bore were planned in lines across the valley, incorporating existing bores (including those in NSW), so that cross sections could be drawn. Holes were planned near irrigated cropping, dryland cropping and native vegetation. The program was conceived to give DERM and QMDC sub-catchment groups a regional monitoring network.

A driller was contracted in 2008 and the program completed in four weeks, supervised by Andrew Biggs (DERM). Holes were generally drilled and sampled to basement of the alluvial and weathered zone (generally <50m), and monitoring bore constructed in the most obvious aquifer. At some sites, a second hole was drilled in shallower layers and a monitoring bore constructed. Data loggers were installed in bores near irrigation to record water levels at sub-daily intervals.

Results

A total of 36 holes were drilled and described (Biggs 2008). Of these 31 were completed as monitoring bores. Saline groundwater was found in 21 bores, 20 of which were sampled for EC and ionic chemistry. Better supplies of shallow saline groundwater were frequently found in irrigation areas, whereas bores in pastured areas were often dry (10 of 31). The presence of acidic saline groundwater was confirmed downstream of Talwood, but at this stage its extent appears limited. The precursors for widespread development of it are however present. In the Lower Moonie, the presence of an eastern palaeochannel downstream of Nindigully was confirmed, and a basement high was found between it and the current Moonie channel.

EC ranged from 9 000 to 57 000 μS/cm and water table depth varied from 6-40 m. Saline groundwater was frequently found at depths <15 m in irrigation areas.

Suspended black material was frequently found in the new bores drilled in the Border alluvia. Initial evidence suggests it may be suspended monosulfides - a precursor to the development of acidity. Further tests are needed to confirm the nature of the material.

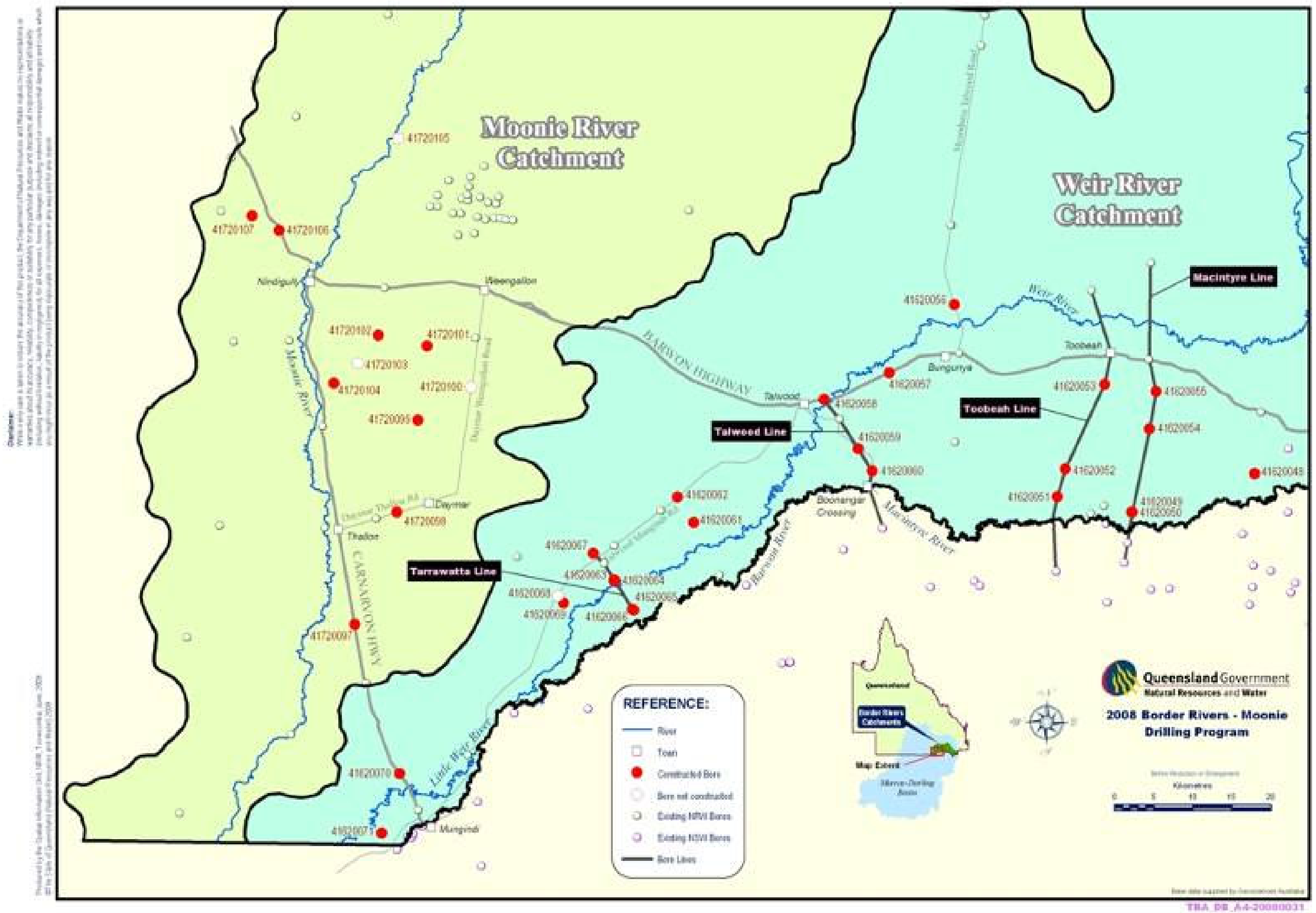

Figure 2. Plan of past (white dot) and new (2008) (red dot) groundwater monitoring sites in Border-Weir and Moonie catchments.

Conclusions

The starting point for implementing the plan outlined above (Table 4) was to undertake the drilling program, to better define the geological stratigraphy and to create a regional groundwater monitoring network. This regional groundwater monitoring network was constructed in the Border Rivers-Moonie during 2008. We will now try to obtain funds to complete other parts of the plan.

Reference

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7. Measuring hydraulic properties of irrigated soils

Introduction

Plant available water capacity

Soil water holding capacity is a key property needed in managing soil water in cropping systems. In dryland cropping in the Queensland and northern NSW grain belt, some 100's of soil have had the soil water holding capacity measured. However, few of these measurements have been made in irrigated systems. Thus few grower would know how much water their soil can hold, in terms of mm (like depth of rainfall) or volume (ML/ha).

Plant available water capacity (PAWC) of the soil is critical in determining soil/water/plant interactions and associated water balance components, including deep drainage. Also, when PAWC is known, we can usually get good results from soil water balance models. PAWC is the amount of water stored in the soil profile that can be used by plants, between the upper and lower limit moisture contents over the depth of rooting (Figure 3, Figure 4). The potential upper and lower limits are related to soil physical and chemical properties. However, the actual lower limit (LL) and the PAWC profile are a function of the maximum extent of root development and the distribution of roots and water uptake with depth. These may be restricted by plant physiology, or soil chemical and physical properties, whichever is most limiting. That is, PAWC depends on soil and plant features. In any particular soil, the lower limit will vary for different plants, as shown by field measurements in Figure 3. On this deep Black Vertosol with few chemical or physical limitations, chickpeas had a lower PAWC and higher lower limit at depth, compared with sorghum, pasture and particularly lucerne.

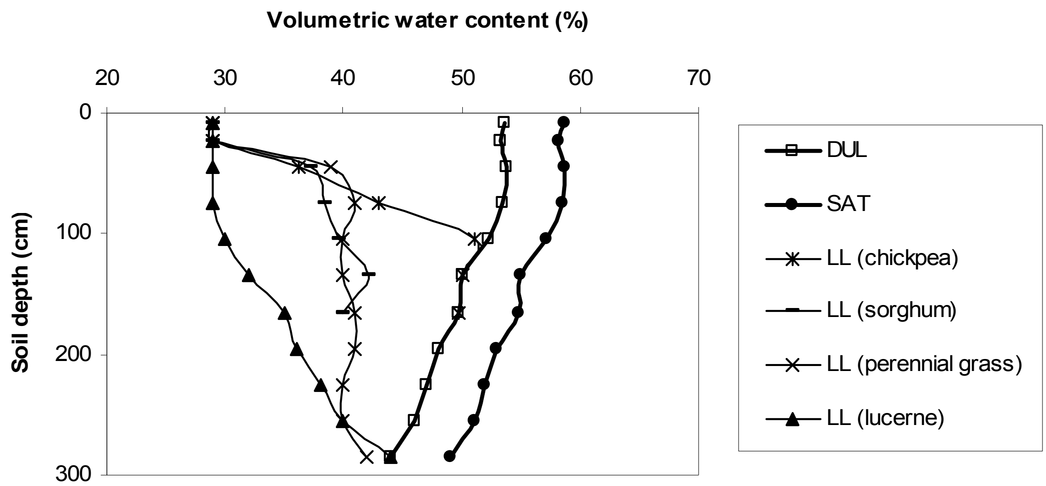

Figure 3 Drained upper limit and crop lower limit for a Black Vertosol (Waco) at Jimbour. (Source: Neal Dalgliesh, CSIRO)

Drained upper limit (DUL) is defined as the moisture content after a soil is fully wet and drainage has practically ceased (sometimes referred to as field capacity). DUL is generally 0.03-0.10 v/v below saturation on swelling clay soils (Gardner 1985) but on coarse textured soil may be as much as 0.3 v/v below saturation (Gardner *et al*. 1998). The water content at saturation

(SAT) is the maximum held in the soil before drainage takes place (Dalgliesh and Foale 1998). SAT is close to the total porosity of the soil, which is directly related to bulk density, but may be slightly lower due to entrapped air. Water between DUL and SAT can drain and is referred to as the drainable porosity. Bulk density is an important soil property as it physically limits the total porosity, SAT and DUL. For swelling clay soils, this should be the bulk density of the soil when fully wet and swollen (i.e. at DUL) (Gardner 1985).

PAWC and the features of the profile (LL, DUL and drainable porosity) can vary widely between soils. For example, PAWC to 1.5 m depth can be as little as 50 mm on a sodic Grey Vertosol to as much as 300 mm on a deep Black Vertosol.

Methods

Three types of measurements have been made (a) PAWC and bulk density profiles, (b) deeper soil coring (e.g. 4-6 m) for in-situ field moisture content and bulk density under irrigated cropping *vs* native vegetation, and (c) moisture retention curves on soil cores taken at various depths in backhoe pits. Each site is located and has morphology described by a soil surveyor and samples are submitted to a range of physiochemical properties. The deep profiles are analysed for pH, EC, Cl and NO^3-N. All data are stored in the NRW SALI soils database.

Measurements have been made on these sites:

1. the Kingsthorpe lysimeter site of Foley *et al*. (in draft) (beside the DEEDI cotton irrigation study of Dr Jose Payero for the project "Maximising Profitability with Limited Water in Cotton Farming Systems" funded by CRDC and GRDC)
2. lysimeter sites of Des McGarry near Dalby, Pampas and Callandoon (west of Goondiwindi). These sites have 3 lysimeters at head, mid and tail locations along the field. The measurements were made near each lysimeter. That is, a total of nine sampling sites
3. two soils west of Talwood on older alluvia contrasting with the Callandoon soils are currently being prepared
4. two soil types west of Condamine/Bell near Dogwood Creek, in collaboration with Olive Hood/Jenelle Hare, to characterise their SIRMOD trial sites
5. similar measurements have been made near the drainage lysimeters at ACRI (Anthony Ringrose-Voase, CSIRO, pers. comm.) and at the sites used by Janelle Montgomery in her PhD – these data are available to us
6. deep cores to 20 m were taken with the geoprobe at McGarry's lysimeter site at Dalby and on a black Vertosol near Brookstead, both in irrigated paddocks and nearby native vegetation. Full soil water, BD, soil chemistry and some stable isotope analysis has been measured on these cores.

To measure PAWC and bulk density profiles, soils were wet up and allowed to drain to DUL, then sampled with a hydraulic coring rig as described by Dalgliesh and Foale (1998) (Figure 4). The in-situ field soil moisture was sampled to 4-6m to determine the moisture status of the subsoil below the crop root zone. Native vegetation was sampled where sites were available. Crop lower limit moisture content was sampled in sorghum, as no cotton was grown in or near the fields that year. LL profiles are available for wheat and cotton at Kingsthorpe and cotton at pampas (data not shown).

All cores were analysed for soil moisture content, bulk density, soil chloride, EC, pH and -15bar moisture content. Soil matrix potential was measured on some soil segments using the filter paper method or a psychrometer.

Figure 4 (a) Wetting up and (b) sampling soil for drained upper limit and bulk density, (c) tensiometers used to check matric potential of the subsoil, (d) sampling in native vegetation.

Results

Water holding capacity

The PAWC profiles are shown in Figure 5 and summaries in Table 5. The Goondiwindi soils had higher bulk densities and therefore lower total porosities, but this did not appear to decrease crop water extraction. The depth of crop water extraction was always deeper than the depth of 1.5 m often sampled. PAWC was about 200 mm, except at the Dalby site with 240 mm. Air content at DUL was around 5%, typical of swelling clay soils, except in sandier layers at the Goondiwindi sites (Figure 5). In the sandier subsoil layers at the Goondiwindi site, DUL decreased while total porosity stayed about the same as in the clay, thus the air content at DUL increased (greater drainable porosity).

The soil at Kingsthorpe was very different, being derived from basalt rather than alluvia, with a low bulk density (1.05) and large total porosity throughout the profile. Lower limit data are available for cotton and wheat. Air content at DUL is high, around 12%. Tensiometer measurements (see Section 8) indicate that the matric potential is near zero when moisture contents are only just wetter than DUL and the effective field saturation (SAT in Figure 5e) is much lower than the total porosity, due to entrapped air.

Table 5 Summary of PAWC data (means of head, mid and tail sites unless indicated).

Site	Soil (ASC)	Local soil name (SPC), Great Soil Group	PAWC (mm)	Depth of water extraction (m) sorghum	Bulk density – mean 1-2m (g/cc)	Subsoil clay % (0.5-0.9m)
Kingsthorpe	Self-mulching Black Vertosol	Craigmore		>1.5m for cotton	1.05	74
Toowoomba	Red Ferrosol	n.d.		1.7	1.44	n.d.
Dalby head,mid,tail	Self-mulching Black Vertosol	n.d.	240	1.9	1.39	65
Pampas head,mid,tail	Self-mulching Black Vertosol	Waco	205	2.4	1.30	73
head,mid	epipedal, Black Vertosol	Undabri(1), Grey Clay	188	1.7	1.60	52 head 64 mid
Goondiwindi Tail	epipedal, Black Vertosol	Undabri(1), Grey Clay	203	2.3	1.69* (* more sandy)	58
West of Talwood	Grey Vertosol	n.d.	In progress	n.d.	1.57	n.d.
West of Talwood	Red/Brown Vertosol	Brown Clay	In progress	n.d.	1.71	n.d.
Western Condamine	Grey Vertosol	n.d.	In progress	n.d.	1.59	59 (0-0.1m).
Western Condamine	Self-mulching Black Vertosol	None suitable	In progress	n.d.	1.83	n.d.

ASC – Australian Soil Classification (Isbell 1996); SPC - Specific Profile Class. n.d. not determined, still to be calculated.

Good quality bulk density measurements allow calculation of total porosity and conversion of gravimetric moisture content to volumetric moisture content and mm of soil water. In the deep coring below the root zone described later, this allowed the unsaturated zone moisture contents to be compared with an absolute reference – total porosity. Without this (or matric potential data), it is common to misinterpret subsoil moisture content data, as demonstrated by Silburn and Montgomery (2004).

Similarly, we use unsaturated zone moisture contents and matric potential under native vegetation as a reference. Except under exceptionally wet circumstances, we expect subsoils under native vegetation to be dry (e.g. -4 to -6 MPa) in inland Queensland.

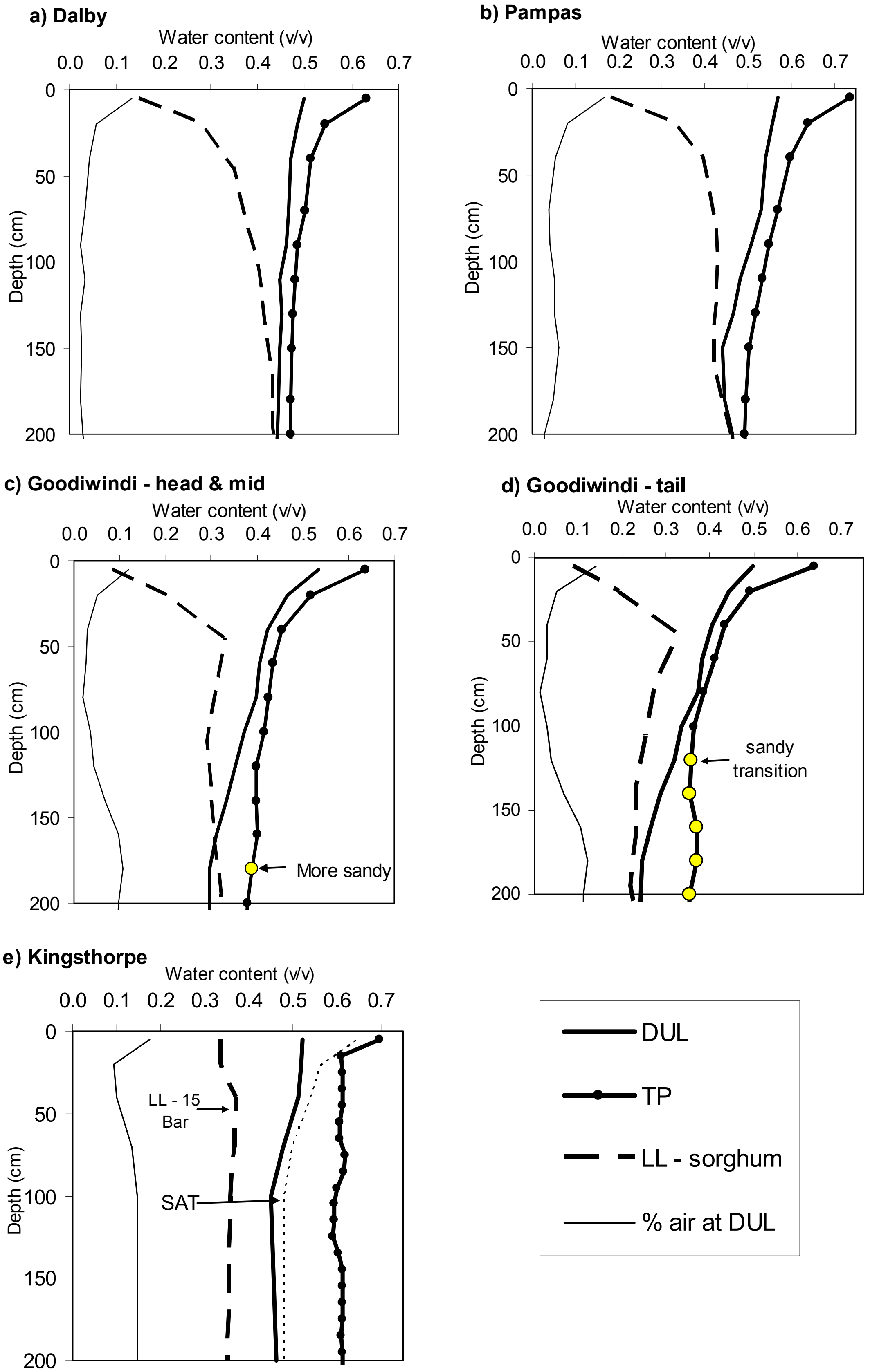

Figure 5 -Total porosity (TP), drained upper limit (DUL), crop lower limit (LL), and air content at DUL for four irrigated sites. Dalby and Pampas are means of head, mid and tail sites; tail shown separately at Goondiwindi as the soil is different to head and mid.

Water retention curves (WRC)

The water retention curve indicates the water content of the soil at a range of matric potentials (suctions) from near saturation to wilting point (-1500 kPa). The WRC is measured on small soil cores by wetting the sample to saturation and progressively equilibrating the soil at increasingly greater suctions, and weighing at each step. The core is then oven dried to determine its bulk density and to convert all weights to volumetric moisture content. Water retention curves were taken at multiple depths in the soil profile for a number of sites, including Kingsthorpe Black Vertosol (Figure 6a), Dalby Black Vertosol (Figure 6b), Pampas Black Vertosol, and Goondiwindi Grey Vertosol. An example set is given in Figure 6. We correct these curves mathematically for overburden, which takes into account the reduction in water content in deep soil layers due to the weight of overlying soil. Water at suctions of 0 to 1 kPa drains easily from the soil while soil water at greater than 1500 kPa (15000 cm) is difficult for plants to remove from the soil.

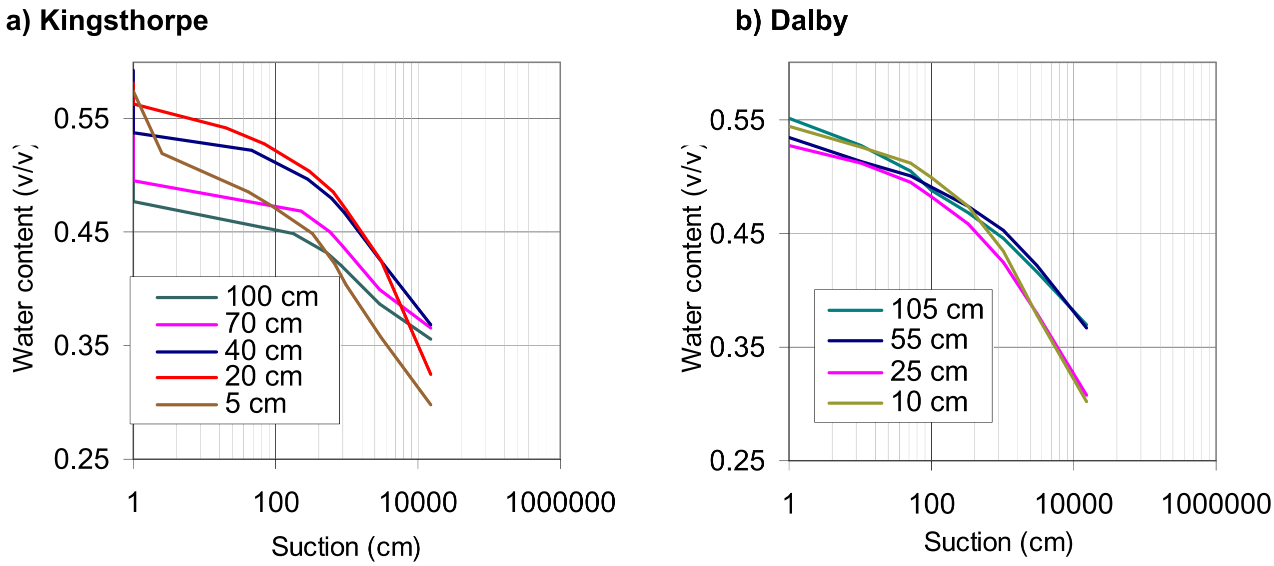

Figure 6. Water retention curves for profile layers of two Black Vertosols, a) Kingsthorpe, with correction for overburden, and b) Dalby without correction for overburden.

WRC's are required for soil water balance modelling when using the class of models which solve the Richards equation (e.g. SWIM, HYDRUS2D, SWAP) and can be used to determine the total porosity, DUL and LL used in 'bucket' soil water balance models (e.g. APSIM, PERFECT, Howleaky?). Deep drainage and groundwater recharge estimation in the Cotton CRC groundwater modelling studies will use the Richards equation type of models (W Vervoort, U Sydney, pers. comm.). The WRC's for the profile at Kingsthorpe, after correction for overburden, are being used by Dr. David Rassam (CSIRO) for HYDRUS2D modelling of the soil water and solute transport in the Kingsthorpe lysimeter soil.

Deeper profiles – where has the deep drainage gone?

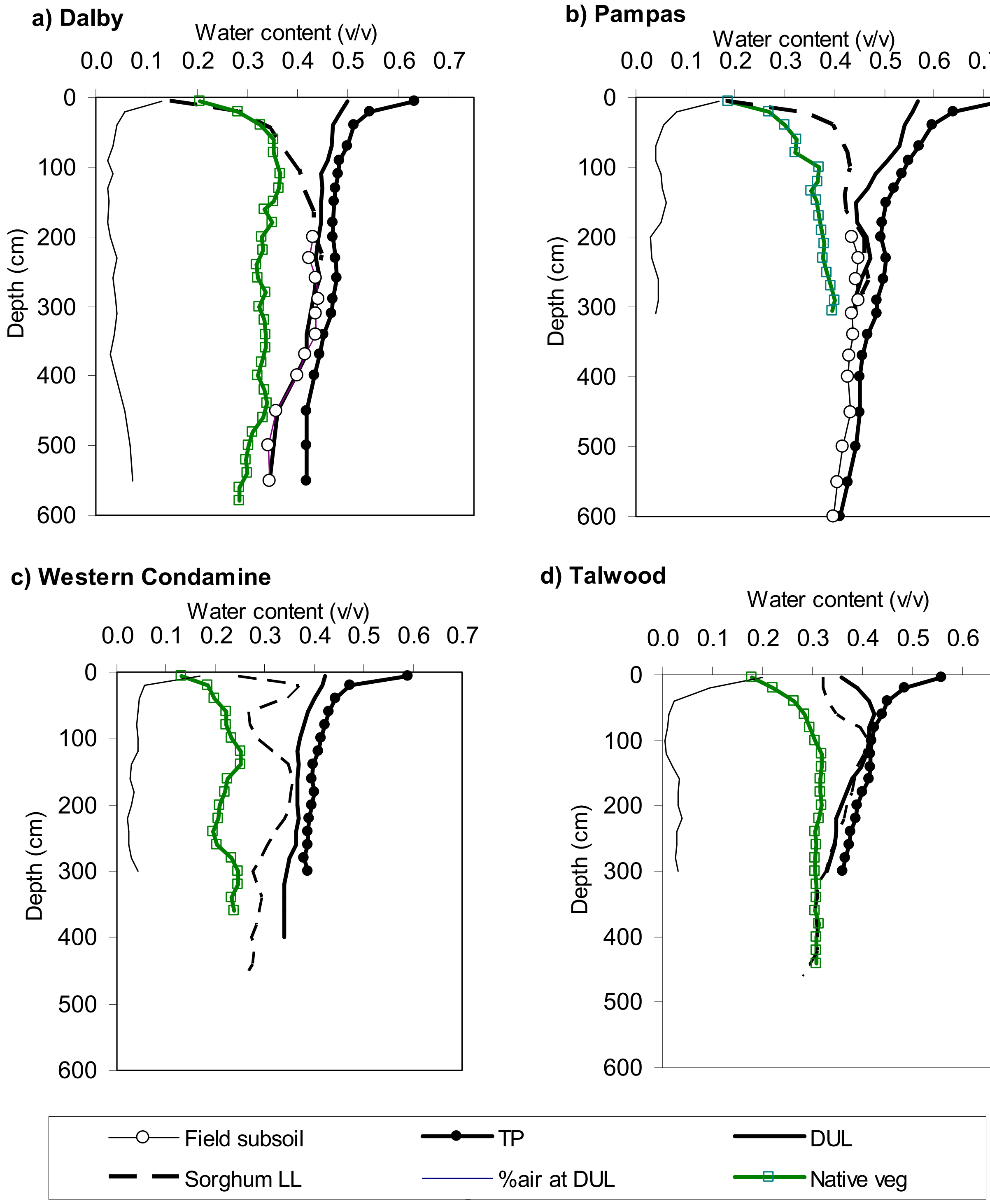

Figure 7 Deep profiles of TP, DUL, LL, air content at DUL and subsoil moisture in irrigated sites and native vegetation (where available).

Four example sites from the deep coring program (taken from a considerably more extensive dataset) have been presented in Figure 7. Deep coring at a number of sites revealed the soil was commonly wet to DUL or above (i.e. activity draining) by 1-2 m depth even after a crop had been grown. This is seen visually in the graphs, where the crop LL curve merges right, towards the DUL and TP curves. This indicates the crop has probably only dried out the top 1-2 m of the profile throughout the irrigated growing season and is also consistent with deep drainage occurring during the season. Beyond 2 m, at most irrigated sites sampled, soil profiles were found to be wet (e.g. Figure 7 a, b). Deeper in the profile, once clay layers begin to intersperse with more sand and silt, there is more drainage. A layer of water logging is often seem above the transition in texture from finer (clay dominant) to coarser (more sand/silt) materials, due to the mechanisms of water movement in porous media (water cannot flow from small pore sizes into larger pore sizes until the layer of finer pores is saturated).

Deeper coring with the geoprobe and more recent coring to 4-6 m with the soil coring rig has provided considerable data to support the widespread occurrence of a historic change in regolith water storage as a result of deep drainage under irrigation. This is further supported by results from the resistivity imaging in the Condamine (Foley et al. 2010), where the widespread occurrence of a layer of near-saturated soil in the profile between 2-6 m was found in irrigated paddocks. This coring has confirmed that deep drainage has been occurring extensively.

Deep coring in native vegetation sites close to the irrigated sampling sites revealed a dryer soil profile under native veg, seen in figure 7 as the green lines. The sample sites were in some instances close to the irrigated paddocks and often a wetter profile was measured under the native vegetation, probably due to long term lateral water movement from the wet paddock into the surrounding drier soil. Generally, the further from the irrigated paddock sampling occurred, the dryer the profile under native vegetation.

The buffer of dry soil created in the regolith under trees (zone between native vegetation LL and DUL, equivalent to tree PAWC, Figure 7) was considerably larger than the crop PAWC. Trees were able to extract more water from the soil, indicted by measured soil water potentials of around 4-6 MPa compared to 1-2.5 for dryland crops, and usually less that this again under irrigation. They were also able to extract water to deeper in the profile. This maintained a 'buffer' against deep drainage losses. For example- there was a buffer of 600 mm to 6 m or 350 mm to 2 m (DUL-LL) under native vegetation at Western Condamine site; and 580 mm to 6 m or 240 mm to 2 m at the Dalby site (Figure 7). This compares to a buffer of only 120 mm and 90 mm, to 2 m, at these sites respectively, in the adjacent irrigated fields.

Current and future work

We are currently building a dataset of joint resistivity imaging, deeper coring and soil chemistry and isotope studies, to trace the deep drainage water further into the unsaturated zone with Bryce Kelly et al. (WRL, UNSW). Resistivity surveys provide a 2-D transect of relative resistivity/conductivity indicating wetter/saltier profiles and drier areas. Conducting the survey at the same time and place as the deep coring allows the resistivity signal to be calibrated and the coring results to be extrapolated along the survey transect. Ionic chemistry and isotope profiles can be used to trace new vs old water down the profile and see the depth of infiltration of the deep drainage water.

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8. Measuring deep drainage under irrigation using a variable suction lysimeter

The variable suction drainage lysimeter (Pegler *et al*. 2003) was developed to overcome some of the artefacts introduced into the measurement of deep drainage by the previous lysimeter designs (Foley *et al*. 2003). It is designed to be 'invisible' to the water flow down through the soil, by tracking and applying the soil suction measured in the surrounding soil. The design has been used in the drainage lysimeter installed at ACRI.

The existing NRW variable suction drainage lysimeter at the Kingsthorpe QDPI&F Research Station was used to study deep drainage under several flood irrigation events, with bromide applied as a tracer. These data and hydraulic properties of the soil measured in-situ (Foley *et al*. in prep. a,b) are being used by Dr David Rassam (CSIRO L&W, Indooroopilly) to model deep drainage and solute movement using the HYDRUS2D model.

Methods

The soil is a self mulching, cracking clay, a Haplic Self Mulching Black Vertosol in the Australian Soil Classification (Isbell 1996) of the Craigmore specific profile class (Harris *et al*. 1999), some 2.6 m deep over basalt. Slope is approx. 0.5%. The lysimeter is beside the QDPI&F cotton irrigation study of Dr Jose Payero for the project "Maximising Profitability with Limited Water in Cotton Farming Systems" funded by CRDC and GRDC.

The lysimeter buried in the undisturbed soil collects water draining from the soil by applying a variable suction like that occurring in surrounding soil (Figure 8). Banks of logged tensiometers in the soil profile record soil matric potential and soil temperature. Soil water probes (Foley and Harris 2007) measure soil moisture continuously. Drainage rates were measured using a (logged) optical drop-counter to measure a real-time drainage hydrograph and leachate samples were retrieved manually (leachate samples collected daily).

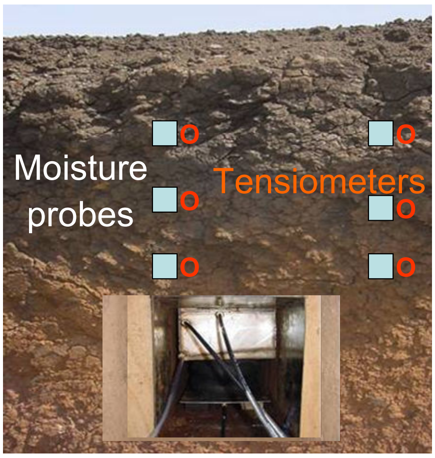


Figure 8. Variable suction drainage lysimeter, tensiometers and moisture probes.

Surface irrigations (containing bromide tracer) were run over the Kingsthorpe lysimeter to measure wetting and draining curves, maximum flow rates, field Ksat, and hydraulic gradient interactions. The experiment consisted of a bromide tracer application, followed by 4 rainfall simulations of 20 mm each, then the first surface irrigation (100 mm), followed 3 weeks later by a second irrigation (120 mm) and tracer application. The surface was covered after the second irrigation and left to drain for 5 months.

Results

Nearly half the water applied to the soil drained below 1 m within 5 months (Figure 9). Of this, 60 mm drained very rapidly, during the first 24-48 hrs after irrigations (Figure 10). A further 30 mm drained more slowly throughout the weeks following ponding.

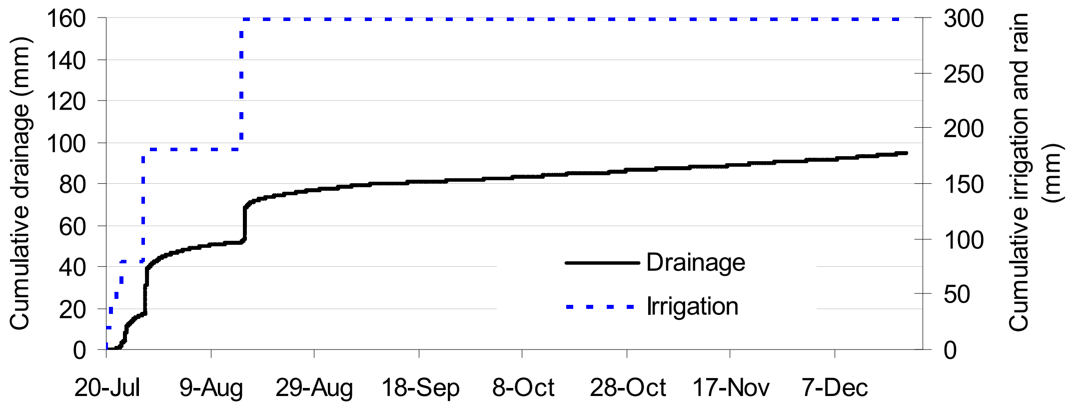
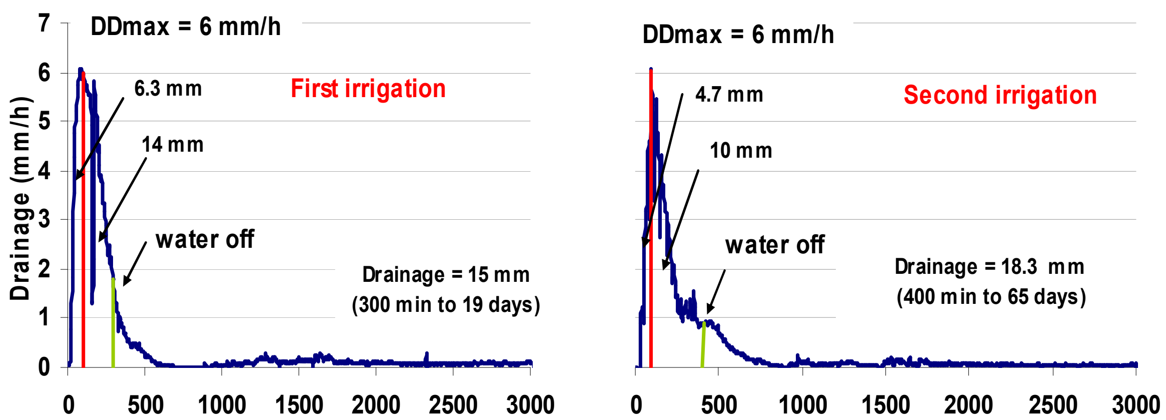


Figure 9. Cumulative drainage during the 5 months after 170 mm water applied as simulated irrigations (4 rainfalls of 20 mm each followed by 2 flood irrigations of 100 and 120 mm each).



Time since start of irrigation (minutes)

Figure 10. Drainage rates measured at 1 m in the soil profile, during and after surface irrigations of 100 mm and 120 mm (first and second respectively)

This drainage tail was considerable, with the profile still draining at a rate of around 40-50 mm/yr (equivalent) 4 months after the last irrigation application. As the plot was covered to prevent evaporation, the surface layers were unable to dry out, which would normally suspend flow (by creating a hydraulic gradient that would pull water up at a greater rate than the force of the gravity gradient moving water down in the profile).

The whole profile was wet to about 'field capacity' prior to starting the irrigation simulations, and so there was very little potential to store water in the profile. The experiment mimics drainage behaviour during the last few hours of an irrigation. The total amount of drainage during each irrigation 18 and 23 mm/irrigation is of a similar order to amounts seen in other studies (Silburn and Montgomery 2004). The potential for drainage through this well structure, non-sodic soil is considerable; particularly during the actual irrigation event when water is being applied. Large gradients in matric potential can move water rapidly through these soils, despite their low saturated hydraulic conductivity, which was measured as 0.6-0.9 mm/hr. Thus the peak flow rates measured (Figure 10) are more than ten times the soils saturated hydraulic conductivity, due to the hydraulic gradient as the wetted front advances through the subsoil.

Under natural rain the maximum drainage rate measured during the study period was 0.82 mm/day. During simulated irrigations, water moved through the soil at a steady rate of 23 mm/day, although peaks of 140 mm/day were measured initially. The surface was only ponded for a few hours during each irrigation. If water had ponded for longer the total DD would have been considerably higher.

Conclusions

Drainage behaviour through a well structured non-sodic heavy clay soil was found to be dominated by large gradients in matric potential during wetting events (e.g. irrigation or large rainfall events). Tensiometry and lysimetry indicate that these large gradients in matric potential can move water rapidly through these soils, despite their low hydraulic conductivity. Previous work (Shaw 1995) indicates that saturated hydraulic conductivity decreases significantly with factors such as subsoil sodicity in Queensland soils used for furrow irrigation. Drainage rates will thus be potentially lower in soils with more sodic subsoils. However, the effects of the driving hydraulic gradients will mean that some drainage will still occur.

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9. Preliminary modelling of water balances for irrigated grains

Introduction

This study was conducted to assist Janelle Montgomery in writing the WaterPAK for irrigated grains. Few measured water balance studies have been conducted in irrigated grains in the cotton growing valleys. Therefore a modelling study was planned to estimate water balance outcomes (irrigation water use, soil evaporation, transpirations, runoff and deep drainage) for grains irrigated by furrow and lateral move/centre-pivot. A useful by-product of simulating the water balance is estimation of crop biomass and yield, and the discovery of relationships between biophysical conditions, management options and crop yields. Here we present some preliminary results.

Methods

We have previously developed (Rattray *et al*. 2004) and applied (Robinson *et al.* 2007 a,b, Silburn *et al.* 2007) a daily soil water balance model based on the PERFECT model (Littleboy *et al*. 1992). It simulates rainfall, irrigation and the fate of water, nutrients and pesticides in cropping systems. This model (HowLeaky?) requires inputs of weather, soil, crop and management conditions. The model is tested against soil water data for an irrigated cotton crop in Mills et al. (2008).
Long-term weather data is available for many stations in the northern Murray-Darling Basin. The period 1960 to 2008 was chosen for simulation because it avoids climate changes present in earlier parts of the long-term record, such as the period with unusually high rainfall in the late 1940s and 1950s.

Soil data was available from a range of studies (see Section 7). The parameters required are concerned with the depth of soil functional layers (mm), runoff potential (curve number), plant-available water capacity (mm), drainable porosity (mm), bulk density (g/cm^3), internal drainage rates (mm/day), and soil evaporation rates (mm and mm/day$^{0.5}$).

Crop parameters required to run HowLeaky? include the rate and amount of development of leaf area index (LAI), root elongation (mm/day) and maximum depth (mm), radiation use efficiency (g/MJ/m^2), harvest index, sensitivity to moisture stress, optimum temperature (^{o}C), thermal time to maximum leaf area and maturity (growing degree days), and base temperature (^{o}C).

Management options were represented by tillage dates, planting dates, and deficits in plant-available water to "trigger" irrigation (mm). Note that irrigation was simulated by "topping up" the soil to its drained upper limit, with no wastage to tail water, and no deep drainage. Any deep drainage that occurs is due to rainfall exceeding the soil water holding capacity. This idealised simulation of irrigation will give better results (lower losses, higher efficiency, higher yields) than real irrigation systems.

The simulations here are for three soils (a Grey Vertosol described in Janelle Montgomery's PhD, a Grey Vertosol at ACRI, and a Black Vertosol studied by David Freebairn at Greenmount on the eastern Darling Downs), and two crops (wheat and sorghum). The weather data is from Narrabri. Only simple annual crop-fallow systems are shown here and pre-irrigation to rewet the soil after a previous crop was not modelled. Double-cropping simulations (e.g. cotton-wheat and sorghum-wheat) are in the last stages of development. Tillage was modelled as zerotill; with high crop yields, stubble cover was high throughout the fallows, reducing soil evaporation and enhancing infiltration.

Results

Irrigated wheat

The annual water balance figures for the three simulated wheat systems are shown in Table 6. Key features of this table include:

- A low irrigation demand – only 1 to 2 in-crop irrigations of 100 mm per year.
- Yields of 6 to 6.7 t/ha/year given sufficient fertiliser inputs and suitable agronomic conditions.
- Deep drainage is high in proportion to the amount of irrigation, but moderate in comparison to furrow irrigated cotton systems where deep drainage is thought to often be 100-200 mm/year (Silburn and Montgomery 2004).
- Deep drainage is greatest on the soil with lowest plant-available water capacity (PAWC, mm).

If deep drainage occurs during irrigation (which was not simulated here), total deep drainage will be greater.

Table 6. Annual simulated water balance and crop yield summary for wheat on three soils.

Soil type	Grey Vertosol (J. M PhD)	Grey Vertosol (ACRI Field 38)	Black Vertosol (D.F. Greenmount)
Plant-available water capacity (PAWC, mm)*	150	195	203
Crop		Wheat	
Deficit for irrigation (mm)		100	
Rainfall (mm)		682	
Irrigation (mm)	146	176	167
Runoff (mm)	44	54	76
Soil evaporation (mm)	348	356	349
Transpiration (mm)	348	381	376
Deep drainage (mm)	85	63	45
Yield (kg/ha)	6050	6530	6660

* these estimates of PAWC assume that the roots can extract water to 1500 mm.

The water use figures are also shown graphically in Figure 11 below.

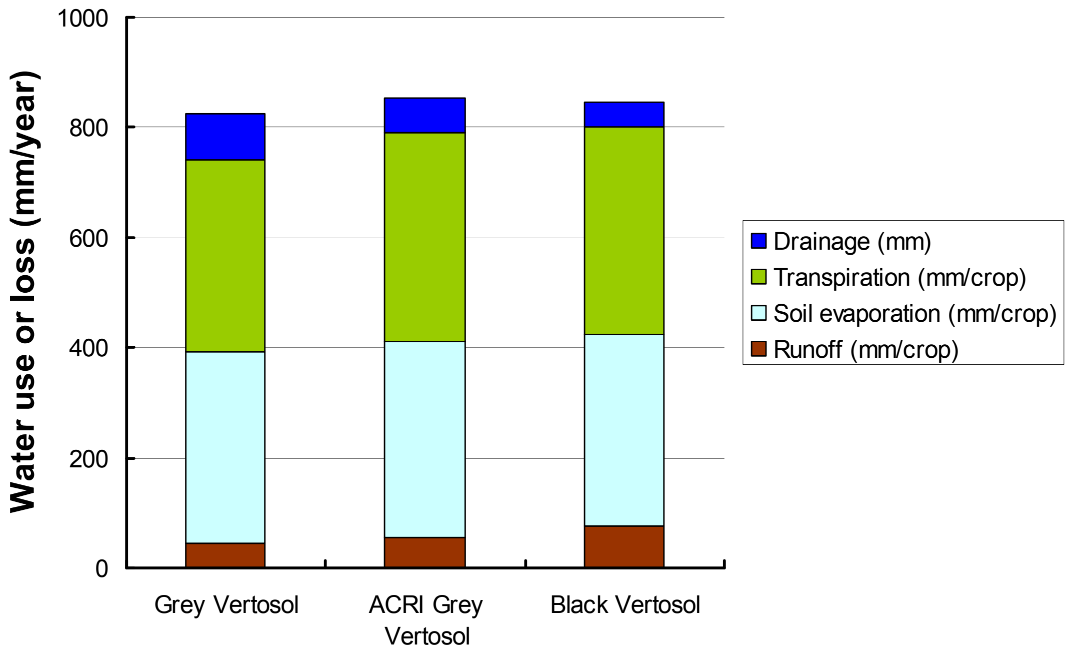

Figure 11. Annual average water use and loss (mm) for irrigated wheat on three soil types at Narrabri.

Deep drainage occurs in the later part of the fallow, due to large rainfall events when the soil is fully or partly wet, and during the winter crop, due to rainfall occurring after irrigation (Figure 12). Deep drainage tapers off as the crop matures and achieves full root development, and irrigation ceased in early to mid September. Irrigation has a early peak in May due to irrigations being triggered by a deficit of 100 mm or more coming out of the fallow in dry years.

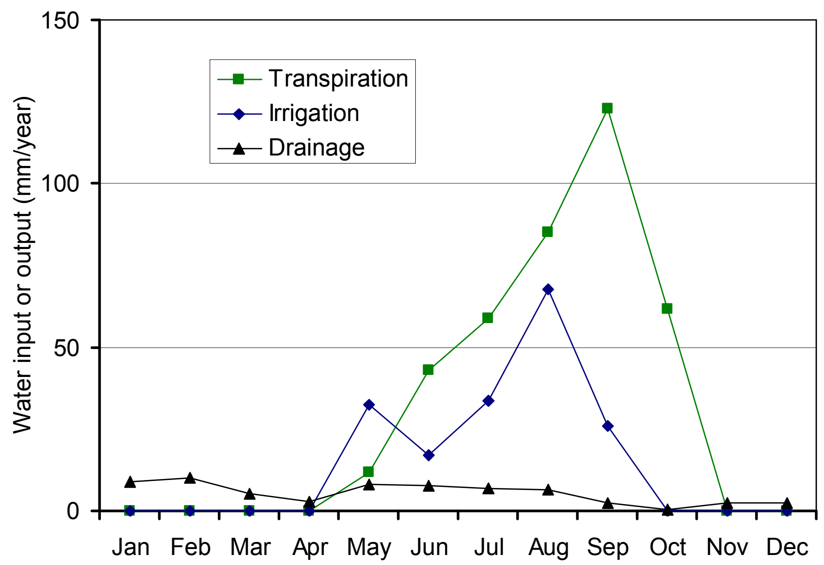

Figure 12. Average monthly distribution of water use, irrigation and deep drainage (mm) for irrigated wheat on the ACRI Grey Vertosol at Narrabri.

Irrigated sorghum

The annual water balance figures for the three simulated sorghum systems are shown in Table 7. Key features of this table include:

- A high demand for irrigation – 4 to 6 in-crop irrigations of 100 mm per year.
- Yields of 10 and 11 t/ha/year given sufficient fertiliser inputs and suitable agronomic conditions.
- Deep drainage is high on the Grey Vertosol with low PAWC, where it is similar to simulations of cotton crops (approx. 100 mm/year). If deep drainage occurs during irrigation (which was not simulated here), total deep drainage will be greater.
- Despite higher irrigation demand, deep drainage is less on the soils with greater plant-available water capacity (PAWC, mm).

In comparison, the wheat system is characterised by higher soil evaporation (associated with summer fallows) and lower transpiration totals, and subsequent yields. Sorghum is characterised by lower soil evaporation, higher transpiration rates and high yields.

Table 7. Annual simulated water balance and crop yield summary for sorghum on three soils.

Soil type	Grey Vertosol (J. M PhD)	Grey Vertosol (ACRI Field 38)	Black Vertosol (D.F. Greenmount)
Plant-available water capacity (PAWC, mm)	150	195	203
Crop		Sorghum	
Deficit for irrigation (mm)		100	
Rainfall (mm)		682	
Irrigation (mm)	489	547	541
Runoff (mm)	32	40	65
Soil evaporation (mm)	272	251	252
Transpiration (mm)	769	870	857
Deep drainage (mm)	98	66	49
Yield (kg/ha)	10100	11400	11200

For sorghum, irrigation follows crop water used closely until the crop matures (Figure 13). Deep drainage occurs in-crop due to rainfall after irrigation, and during the winter fallow due to large rainfall events when the profile was partly or fully wet.

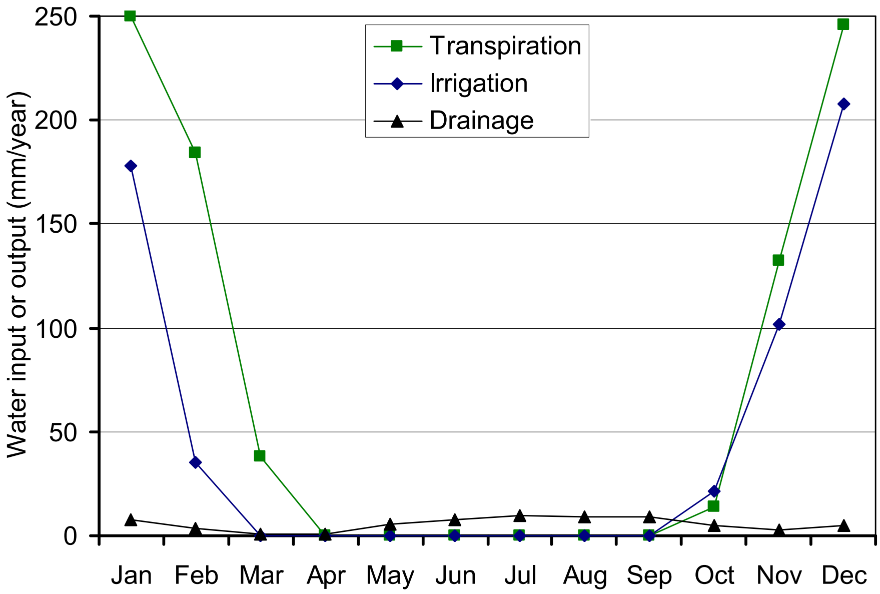

Figure 13. Average monthly distribution of water use, irrigation and deep drainage (mm) for irrigated wheat on the ACRI Grey Vertosol at Narrabri.

Conclusions

These simulation studies provide detailed estimates of the components of the water balance. Advantages include estimating the water balance:

- over many years, whereas field studies usually last for a few years,
- of all of the components, not just runoff or deep drainage,
- of difficult-to-measure components, such as deep drainage, transpiration and soil evaporation,
- · at low cost, and
- · of many different farming systems.

The disadvantages include:

- · a fundamental disbelief concerning models by some people,
- · a lack of real-world connectivity ("richness") in the results, such as not having photos from field sites, and
- a lack of measures of accuracy or statistical uncertainty to go with the results.

Overall, this work shows that the HowLeaky? model or other soil water balance models might be successfully used to investigate relationships between management options such as irrigation frequency and amount, and components of the water balance that we wish to manage, such as deep drainage.

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10. Abstracts from accompanying publications, drafts, reports

Deep-drainage through Vertosols in irrigated fields measured with drainage lysimeters

Gunawardena TA[1], McGarry D[1], Robinson JB[2], Silburn DM[2] (2010),
Accepted Australian journal of soil Science
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2Department of Environment and Resource Management, Toowoomba Qld.

Abstract: Rising groundwater and salinity is potential risk across irrigated agricultural landscapes. Water is scarce in many areas, leading to benefits from efficient water use. Deep drainage (DD, mm) beneath irrigated crops is undesirable because it may cause salinity and decrease water use efficiency. Nine irrigated commercial cotton fields (eight furrow irrigated and one spray, lateral move irrigated) were selected in the upper Murray Darling Basin (UMDB), on Vertosols with a wide range in clay contents (38 – 75%). Barrel lysimeters were installed to capture water passing 1.5 m depth at three positions: (i) near the head ditch, (ii) in the middle of the field, and (iii) close to the tail ditch. At two sites, infiltration along the length of the field was monitored in two seasons using furrow advance-SIRMOD methods.

Seasonal DD values of up to 235 mm (2.35 ML/ha) were measured (range = 1mm to 235mm). This is equal to 51% of the irrigation amount at that location in that season. Individual DD events greater than 100 mm accounted for 14 of 66 measured values. DD varied strongly along the length of each field with DD commonly reducing from the head ditch to the tail ditch. SIRMOD simulation mirrored this trend with large differences in infiltration amounts from head to tail. Greater DD at the head locations was attributed to long periods of inundation, especially early in the season when siphons (in-flows) were allowed to run for up to 24 hrs. DD was greater at tail location on one occasion at one site when a tail drain blocked, causing inundation. Inter-season variation of DD was large - limited water supply in drought years led to fewer irrigations with smaller volumes, resulting in little or no DD. Therefore, control of DD under furrow irrigation can be achieved by changing irrigation management. DD under the lateral move was almost zero; only one irrigation event in 4 years resulted in DD. Spray irrigation with a lateral move irrigator appears to be an attractive alternate method of irrigation where DD must be minimized. In these this case, yields were maintained with dramatically reduced irrigation water usage. Across all the lysimetry sites, high salinities (EC, dS/m) of the DD leachate indicate that large amounts of salt are being mobilised. The fate and impacts of this salt are largely unknown.

Electrical resistivity to quantify soil moisture in clay soils in the field—which accuracy is realistic?

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Abstract The accuracy of soil moisture estimates based on ERI, utilising commonly used inversion routines, current quantitative resistivity interpretation models and levels of soil sampling that are realistic for routine applications is assessed and the main sources of uncertainty are determined. Soil moisture depth profiles are derived for two sites on Black Vertosols based on ERI images, two selected resistivity interpretation models and soil sampling results. Moisture estimates based on different restrains on the inversion routine varied between 5% at the top of the profile and 27% at the bottom of the profile, indicating the importance of an optimisation of the inversion routine. Differences in soil moisture estimates based on the default and the optimised inversion results varied by 2 to 7%, indicating that in this study the default inversion setting gave reasonable results. Uncertainties in the soil parameters directly influenced the resulting soil moisture estimates. An increase in the soil parameter values of 10% resulted in an average decrease of the soil moisture estimate of 13 and 14% for the two sides, a 25% increase of the soil parameter values resulted in an average decrease of 31 and 34%, respectively. Variations introduced into the soil moisture depth average by either not fitting the resistivity interpretation model or using a 2nd interpretation model were on average only 2%.

Resistivity imaging across native vegetation and irrigated Vertosols of the Condamine catchment—a snapshot of changing regolith water storage

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Abstract Over use of one of Queensland's most productive groundwater systems, the Condamine River alluvium, has led to substantial depletion in groundwater levels. Most use is for irrigation (mainly furrow), which is known to increase deep drainage below the root zone. Thus irrigation should create greater groundwater recharge, but this is not generally detected in groundwater levels. The enhanced deep drainage may be filling a moisture deficit in the unsaturated zone and is therefore not yet causing greater recharge.

Geophysical 2D resistivity imaging and soil coring was used to look at changes in stored regolith water in the alluvium. Transects were imaged across naturally vegetated landscapes (as a reference) into irrigated paddocks. All soils under native vegetation were found to be very dry (low conductivity) even when only sparsely populated by trees. In contrast, significant long-term migration of water has occurred to deep within the regolith (up to 15 m) in most irrigated paddocks. A wet (close to saturated) zone was found in the upper 6 m of soil in the irrigated paddocks. Deeper regolith (20-60 m) was resistive, both above and below the water Table, due to low salinities in the groundwater and coarser textures.

Root zone soil moisture content in a Vertosol is accurately and conveniently measured by electromagnetic induction measurements with an EM38

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Abstract It is sometimes preferable to measure soil moisture content without destructive sampling or equipment installed in the field (as required for TDR probes and neutron probes). Electromagnetic induction (EMI) instruments are lightweight and portable, and measure apparent soil electrical conductivity (ECa), which is affected by moisture content. The EM38 is an EMI meter that is usually used for mapping salinity. As well as salinity and soil moisture, EMI meters respond to factors including clay content, soil temperature and magnetic minerals. Assessing the importance of these factors, and negating them where possible, would be a significant step toward using EMI for routine soil moisture measurement. This study shows that EMI measurements can accurately predict soil moisture content at a range of depths.

SUMMER SCHOLARSHIP
Final Report
Project Number 5.10.03.17
Project title "Improved measurement of soil water under irrigated cotton"
Mills T, Foley JL, Robinson JB, Silburn DM, Misra R (2008)

Aims and milestones: This project aims to provide detailed measurements of soil water and distribution of irrigation water and changes to the water balance of an irrigated cotton system, during a summer growing season.

Infiltration of irrigation water, and soil water extraction by plants, are key components of the water balance of cotton crops. They are difficult to measure because measurements need to be repeated over time and made at a range of depths in the soil, and because access is difficult when fields are wet. Because our modelling studies of the water balance of cotton crops require this basic information, we wished to trial measuring infiltration and extraction throughout an irrigation season using electromagnetic induction methods (using an EM38 device) to track water content changes across a paddock where spatially variability occurs due to furrow irrigation. That is, soil water may vary from the head to the tail ditch and between furrows. An important innovation will be to use the depth response function of the EM38, in conjunction with measurements of the soil water profile obtained from soil coring, to give depth discrete soil water profiles ('depth slicing' as done for airborne EM).

The summer scholarship student was required to calibrate the EM38 at an established study site in SE Qld and monitor water changes during consecutive irrigation sequences in the summer growing period.

Salinity in Queensland—hydrologic change from soils to catchments

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Introduction Salinity is an insidious environmental issue. Its expression can be greatly removed in time and space from its origin and it can take a lot longer to fix than to cause. In this paper, we summaries new aspects of hydrology and salinity in catchments in Queensland, which were explored over the last decade, in particular in the Darling and Fitzroy Basins. Determining the progress of hydrologic change after land use change, and understanding useful indicators of change, was of particular interest, as long time lags may occur between change in land use and responses in stream and land salinisation.

Losses of soil chloride provide an early indicator of hydrologic change, whereas changes in groundwater are an intermediate indicator, and increased salt exports from large catchments are a late stage indicator. Key findings relating to the following will be discussed:

(1) Deep drainage at the soil profile level using transient chloride mass balance, lysimetry and soil water balance modelling,
(2) Moisture status of the unsaturated zone,
(3) Groundwater responses to rainfall,
(4) Catchment salt balances and flow duration,
(5) Risk assessments across large river basins.

Deep drainage myth-busters

Emma Brotherton1, Graham Harris1, Peter Smith2 and David Wigginton2
DPI&F1 and NSWDPI2

Myth 1: When I irrigate throughout the season the soil seals, reducing infiltration - so how can I have Deep Drainage? – Page 2
Myth 2: Groundwater tables have been falling over the last few years, how can we have deep drainage? – Page 4
Myth 3: My soil moisture measurement tool does not show a change in soil water levels at depth throughout the season – this means deep drainage is not occurring. – Page 5
Myth 4: My water storage does not leak so deep drainage is not an issue when I irrigate. –Page 7
Myth 5: I irrigate efficiently by maintaining high heads and pulling siphons as they come through so no deep drainage occurs. – Page 8

GROUNDWATER MODELLING STUDY BORDER RIVERS FLOODPLAIN QUEENSLAND

Project report submitted for: Masters of Science in Hydrogeology and Groundwater Management 2007

By David Whiting, BApp Sc (Hons)

ABSTRACT Recent investigations of the Border Rivers region have indicated rising groundwater levels in crop irrigated areas and widespread high groundwater salinities. A preliminary groundwater salinity assessment was undertaken in a region subjected to crop irrigation on floodplain alluvium between Weir, Macintyre and Barwon Rivers in Queensland. A single layered numerical groundwater model of the floodplain alluvium was developed to identify areas susceptible to groundwater emergence and salinisation.

The hydrogeological assessment of the region indicated that floodplain alluvium is generally 20 to 30m thick and spatially highly variable in lithologies varying from clay to coarse sand/gravel layers. Groundwater levels are sympathetic to topography and indicate an unconfined system. A steady state groundwater model was developed. The model was calibrated against groundwater heads with groundwater contours interpolated from measured groundwater levels across the region providing a hydraulic conductivity range of 5 to 50 m/d for the saturated alluvium. A series of transient state scenarios were simulated applying specific yields of 0.15 to 0.30, hydraulic conductivity values of 5m/d and 50m/d and surface recharge rates 0.1, 1 and 10 times the deep drainage rates for different soil and land use types derived from soil water balance modelling results from Department of Natural Resources and Water (DNRW).

Results indicated near surface groundwater mounding and surface groundwater emergence was characterised in areas with a combination of a) crop irrigation and b) shallow depth from surface to starting groundwater heads. These areas were generally in the south to southwestern part of the project area near Barwon River where starting groundwater heads were shallower. Shallow groundwater mounding and surface emergence was most sensitive to hydraulic conductivity and surface recharge rate applications.

The assessment highlighted deficiencies in available spatial and temporal groundwater data, topographical elevation data and hydrogeological data produced major uncertainties in characterising the groundwater regime for the region and modelling resolution. There was insufficient spatial and temporal groundwater salinity data to discriminate vertical or horizontal salinity zoning.

Recommendations for further work to improve resolution of modelling groundwater salinisation outbreak in the region include a) targeting field drilling and groundwater monitoring in areas identified through this modelling as susceptible to shallow groundwater mounding and surface outbreak; b) improve hydrogeological conceptual model of region by conducting drilling investigations to characterise layering within the alluvium and hydraulic interaction between underlying Griman Creek Formation and the alluvium; c) conducting more detailed elevation survey surveys, particularly along the major rivers reaches; d) groundwater investigations to asses river interaction with groundwater system; e) improve groundwater spatial and temporal data resolution across the region by installing more observation bores and monitoring more frequently; f) introduce more paired control and irrigated monitoring groundwater stations; and g) characterise saturated alluvium hydraulic properties by conducting single borehole testing or pumping tests on established bores or strategically placed bore sites.