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Planning Assessment Commission Meeting to consider both Bibblewindi and Dewhurst Gas Exploration Pilots, Narrabri Shire
Date & Time: 9 am, Thursday 19 June 2014
Place: Narrabri Bowling Club, 176 Maitland Street, Narrabri

Address: Nicky Kirkby "Koiwon" Bellata NSW 2397 0429968237

I would like to bring to your attention the views of the 93% of farmers in the Bellata to Millie and south district who voted not to have CSG within their farms or roads or district.

These framers are mostly broad acre cropping dryland or irrigated farmer's; highly sophisticated leaders in their field world wide.

- The average capital asset base is $3,800/Ha
- The returns are between 6 – 7% avg. with the top performers over 10% before capital gains which if included at 8% put them up to 14.5 – 18% returns.
- Irrigation offers high security enabling forward selling of crops including cotton etc maximising opportunities to compete in the world market, where most of our competitors and their support industries are highly subsidised

ABARE average return for famers across Australia is 2 – 3%

Narrabri and Moree Shires are unparalleled with any other shire in Australia for agricultural returns 2.5 times greater than their closest competitor.

So as you can see these farmers have invested heavily into protecting their asset base; water, soil structure/health, the balanced ecology and the communities who service them. These farmers understand the meaning of balance; they also at no cost to the public provide many ecosystem services such as clean air, water and viable healthy communities.

Farmers here understand the cycles of seasons; droughts/floods, varying rainfall, market fluctuations and other variables that impact both positively and negatively on their ability to make a return and as such they have developed their crop sequences to hold water and maintain soil properties with a view to a three to seven year rotation i.e. so what they do now (replacing organic mater, providing stubble, cover cropping, disease mitigation etc) will be with a view to what they will be doing in three to seven years – in order to hold water and maintain soil properties while accommodating all the previously mentioned variables.

So my reason for mentioning this, is to try to let you understand these farmers manage today for what will happen in the long term, and their long term is also cyclic; it is intergenerational - so 20 – 30 yrs, 3 – 6 cycles. There is no time to make mistakes, rest on your laurels, take short cuts. If you do, as most farmers will tell you it will come back to bite you and the bite will be big and take another 1- 2 cycles to recover.

So everything they do is with a view for the long term sustainability. No place in the world where I have been is this more pronounced than this district and it is the very reason I chose to build my life and raise my family here. Looking at sustainability more closely determines why the farmers I represent and others I am sure object strongly to CSG and extractive industry.

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I should at this stage also point out the lack of good science involved in these decisions is horrifying at best.

Where there is good science it tells us that there are definitely relationships between aquifers and surface and groundwater, however how that happens, the variation and speed at which recharge occurs is not determined.

The mapping below ground is not guaranteed. It is modelling using ground truthing by point source data that may be very large distances apart. The manner in which ground water moves through soil and subsoil can only be measured accurately by using Lysimeters to a relatively short distance below ground level.

EM Surveying works on densities and then best estimates are applied to the densities. There is much discrepancy identifying actual soil/ water properties at this stage.

"Report onNorthern Murray-Darling Water Balance Workshop 2. ***'Deep drainage – so what?'*** *'Where is it going and what is it going to do and when?'Narrabri, 19 – 20 November 2003; Silburn DM, Vervoort RW, Schick N for the Northern Murray-Darling Water Balance Group 2004 (Coordinated Multidiciplinary specialist group of 12 – 30 people research review which happened annually over ten years) and later "****Aquifer heterogeneity and response time: the challenge for groundwater management"*** *B. F. J. Kelly A,B,C,D,I, W. A. TimmsA,B,C,E, M. S. AndersenA,B,C,F, A. M. McCallumA,B,F, R. S. Blakers A,C,G, R. SmithA,H, G. C. RauB,C,F, A. BadenhopF, K. LudowiciC,F,*
and R. I. AcworthA,

So why aren't the scientists standing up?

1. This is a multidisciplinary question
2. Scientists are restricted in what they can say or have approved by their employers. A good example of this is the CSIRO Multi million dollar program GISIRA (Gas Industry Social & Environmental Research Alliance) looking into the implications of CSG co funded by Australia Pacific LNG and QGC and with a publication approval process straight past LNG Management. This program was developed with a view to informing politicians industry and others under the seemingly independent auspices of CSIRO (Australia's premier science provider)!

Our farmers know all this and they also know about failed bores, how long it takes to make good an out of balance ecosystem etc. They also know about the untold details of potential risks, the cover ups, over exaggeration of employment and other benefits to the community of the lack of transparency, the many unscrupulous operations that Santos have undertaken and been found out etc,

So while we can debate about the extent of details and where the science is/ is not, what we know about CSG is it is:

- short term
- Invasive – to the land and water ecosystem services and to the land in its above ground physical presence, and to the communities who rely on the land.

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Risky: - it has many risks unquantified

- water, ecosystems, soil structure, sub soils structure
- ecological
- community/ social dynamics (health, economics long term)

If you were to be looking at a risk matrix to help clarify the decision it would be categorised as either Extreme of at very least High *(attached example of a standard Risk Matrix from the govt of South Australia web site)*

These effects of CSG may not be obvious immediately but maybe more so in ten to twenty years following, at which point

- What will be the mitigation strategy? - NONE
- Where will the politicians be then?
- Where will the CEO of Santos be then? CEO of what? New bonuses to chase!

They are all the short term thinkers who buy time to sure up their argument or exit their responsibilities.

It is then little wonder that; these farmers are insulted at the governments short term view to allow this industry to develop; that these farmers are crying on the inside at what this might mean for their children and the communities they may or may not be living in.

I ask you to think hard about the values that our government is promoting by considering this industries 'go pass' and I ask you to please recognise the values and attributes of these farmers who:

- Work hard when it is needed for however long.
- Are resilient
- Have a healthy respect for life and its balances
- Who are unrivalled custodians of the land providing many public benefit ecosystem services at no cost to the government.
- Who are the people in this debate who have a long term view and commitment and who will be there at the finish/ or not – worst case.

These people are your elders; they have generations of experience and knowledge of the systems, land and water and social understanding of this area, where science has been limited due to in part, to preferred government offices for science or landcare etc being further east.

They are the pillars of rural communities they keep the balance.

When farmers become protesting environmental radicals, listen to them.

~~In history there is no time the government has gone wrong by listening to the farmers with regard to sustainability.~~

Christine Lagarde CEO Internationall Monetary Fund said in a

over

Government of South Australia
Department of Education and Children's Services

RISK ASSESSMENT MATRIX
Determining the Level of Risk

This document can be used to identify the level of risk and help to prioritise any control measures.
Consider the **consequences** and **likelihood** for each of the identified hazards and use the table to obtain the risk level.

			Consequences				
			1 – Insignificant Dealt with by in-house first aid, etc	**2 – Minor** Medical help needed. Treatment by medical professional/hospital outpatient, etc	**3 – Moderate** Significant non-permanent injury. Overnight hospitalisation (inpatient)	**4 – Major** Extensive permanent injury (eg loss of finger/s) Extended hospitalisation	**5 – Catastrophic** Death. Permanent disabling injury (eg blindness, loss of hand/s, quadriplegia)
Likelihood	A	Almost certain to occur in most circumstances	High (H)	High (H)	Extreme (X)	Extreme (X)	Extreme (X)
	B	Likely to occur frequently	Moderate (M)	High (H)	High (H)	Extreme (X)	Extreme (X)
	C	Possible and likely to occur at some time	Low (L)	Moderate(M)	High (H)	Extreme (X)	Extreme (X)
	D	Unlikely to occur but could happen	Low (L)	Low (L)	Moderate(M)	High (H)	Extreme (X)
	E	May occur but only in rare and exceptional circumstances	Low (L)	Low (L)	Moderate (M)	High (H)	High (H)

How to Prioritise the Risk Rating

Once the level of risk has been determined the following table may be of use in determining when to act to institute the control measures.

Extreme	Act immediately to mitigate the risk. Either eliminate, substitute or implement engineering control measures.	Remove the hazard at the source. An identified extreme risk does not allow scope for the use of administrative controls or PPE, even in the short term.
High	Act immediately to mitigate the risk. Either eliminate, substitute or implement engineering control measures. If these controls are not immediately accessible, set a timeframe for their implementation and establish interim risk reduction strategies for the period of the set timeframe.	An achievable timeframe must be established to ensure that elimination, substitution or engineering controls are implemented. NOTE: Risk (and not cost) must be the primary consideration in determining the timeframe. A timeframe of greater than 6 months would generally not be acceptable for any hazard identified as high risk.
Medium	Take reasonable steps to mitigate the risk. Until elimination, substitution or engineering controls can be implemented, institute administrative or personal protective equipment controls. These "lower level" controls must not be considered permanent solutions. The time for which they are established must be based on risk. At the end of the time, if the risk has not been addressed by elimination, substitution or engineering controls a further risk assessment must be undertaken.	Interim measures until permanent solutions can be implemented: • Develop administrative controls to limit the use or access. • Provide supervision and specific training related to the issue of concern. (See Administrative Controls below)
Low	Take reasonable steps to mitigate and monitor the risk. Institute permanent controls in the long term. Permanent controls may be administrative in nature if the hazard has low frequency, rare likelihood and insignificant consequence.	•

Hierarchy of Control   Controls identified may be a mixture of the hierarchy in order to provide minimum operator exposure.

Elimination	Eliminate the hazard.
Substitution	Provide an alternative that is capable of performing the same task and is safer to use.
Engineering Controls	Provide or construct a physical barrier or guard.
Administrative Controls	Develop policies, procedures practices and guidelines, in consultation with employees, to mitigate the risk. Provide training, instruction and supervision about the hazard.
Personal Protective Equipment	Personal equipment designed to protect the individual from the hazard.

Australian Government
Land & Water Australia

Final Report

Coordinating Deep Drainage Research in the Northern Darling Basin

Nicky Schick, Australian Cotton CRC

Project: Coordinating Deep Drainage Research in the Northern Darling Basin (CRD2)

National Program for Sustainable Irrigation

Product code PN21997

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Final report

Coordinating Deep Drainage Research in the Northern Darling Basin

Australian Cotton Cooperative Research Centre

Australian Government
Cotton Research and Development Corporation

NATIONAL PROGRAM FOR
Sustainable Irrigation

Funded by Land and Water Australia through the National Program for Sustainable Irrigation (NPSI)

Project Reference	CRD2
Research Organisation	Australian Cotton CRC / CRDC
Program	Sustainable Irrigation Program
Project Title	**Coordinating Deep Drainage Research in the Northern Darling Basin**
Principle Investigators	Nicky Schick, Australian Cotton CRC
Project Duration	30/9/2003 – 1/07/2005
Report author	R.W. Vervoort, McCaughey Senior Lecturer Hydrology and Catchment Management, University of Sydney / Australian Cotton CRC
Collaborators	Vervoort, R.W. (U Syd), Silburn, M and McGarry D (NR&M Qld), Hulugalle, N (NSW DPI), Ringrose Voase, A (CSIRO), D Gibb/B Pyke (CRDC), G Fitt/ G. Roth (Cotton CRC)

Due Date for Final Report 1/10/2005

Project Objectives

1. Develop agreed understanding by peak stakeholders of deep drainage in the Northern Darling Basin.
2. Develop clear and agreed gaps in knowledge and how to overcome them.

Alteration to original objectives – none

List of acronyms

ACCRC	Australian Cotton CRC
ACRI	Australian Cotton Research Institute (Narrabri)
BMP	Best Management Practice
CCC CRC	Cotton Catchment Communities CRC
CMA	Catchment Management Authority
CRDC	Cotton Research & Development Corporation
DIPNR	NSW Department of Infrastructure, Planning and Natural Resources
EM	Electromagnetic Induction
NMD – WBG	Northern Murray Darling Water Balance Group
NSW DPI	NSW Department of Primary Industries
NR&M	Natural Resources and Mines, Qld.

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1. Abstract

A key issue identified by the research community working with the cotton industry was the lack of understanding and acceptance of the concept of deep drainage. The Northern Murray Darling – Water Balance Group (NMD – WBG) was conceived as a partnership of researchers and extension personnel to exchange ideas, create awareness and debate the issue of deep drainage in the Darling basin. The aims of this project were to achieve consensus and identify research gaps and opportunities to overcome these gaps. In the course of two years the members of the NMD – WBG held two major workshops, organised or attended 25 stakeholder meetings, gave a plethora of presentations to various groups, published papers, prepared extension materials and communicated with the wider public.

The key achievements of this project are: Broad agreement was achieved in the cotton industry about Deep Drainage as a management issue; key research gaps were identified; recommendations for research were formulated; initial projects were funded by CRDC/CRC, outcomes were communicated in papers, extension materials and the media; two major workshops were held and new collaborations established with researchers; links were established with other industries such as grains; research reviews were written; deep drainage was included as a management issue in the Cotton Industry's BMP Land and Water Manual; and a new coordinated research program which covers landscape impacts of cotton irrigation on ground and surface water has been established (Program 2 - The Catchment) in the new Cotton Catchment Communities CRC.

2. Introduction

A key issue identified by the research community working with the cotton industry was the lack of understanding and acceptance of the concept of deep drainage. Deep drainage is defined as the part of the water (applied to the surface and as rainfall or irrigation) that moves past the rootzone. In general the existing paradigm was "cotton soils don't leak". However, the research community related to the Australian Cotton CRC (ACCRC) was well aware of observations and simulations indicating significant deep drainage under irrigation. Examples of such studies include the PhD work by J. Montgomery in the Gwydir Valley, measurements by Willis et al. (1997) in the Macquarie valley and estimates by Weaver et al. (2004) in the Namoi valley. However, the estimates range widely and there was some disagreement about the magnitude of deep drainage and its impact. However, from logical considerations based on water quality and leaching fractions (Vervoort et al., 2003) it could be expected that at least 10% of the applied irrigation water is lost below the rootzone.

While it was unknown what the future implications of this deep drainage might be in terms of landscape salinity, it was agreed that there was a need for more accurate measurements and that there was a need to create awareness about deep drainage in the cotton industry and forge linkages with researchers from other industries. Rather than reinventing the wheel, it was important to link to research on deep drainage in other agricultural industries. But due to the differences in climate and soils between the northern and southern part of the Murray Darling Basin, not all established research was directly useful.

The Northern Murray Darling – Water Balance Group (NMD – WBG) was conceived as a partnership of researchers and extension personnel to exchange ideas, create awareness, and debate the issue of deep drainage. This project provided logistical support to help the group achieve these goals.

3. Activities

The key role of the NMD – WBG was in communication, that is, its members concentrated on communicating research about deep drainage to fellow researchers and stakeholders.
The activities of the NMD – WBG therefore fell into three categories:

- General communication (presentations, publications and press releases) and building relationships with other industries, for example, dryland counterparts such as grain growers (see Appendix 1);
- Active participation in around 25 stakeholder meetings in relation to deep drainage with NSW Catchment Management Authorities (CMA's) and Qld Regional Bodies to raise the issue of deep drainage;

- Organisation of 2 technical workshops in relation to (1) lysimeter studies and (2) consequences of deep drainage and groundwater-surface water interactions.

The major event was a 2 day workshop on consequences of deep drainage and surface water-groundwater interactions in relation to irrigated agriculture in the Northern Murray Darling Basin. The focus of the workshop was to identify knowledge gaps and find agreement on research needs and directions. The workshop was attended by more than 60 attendees from different organisations including Federal and State organisations and research providers and industry. A report on the findings of the workshop was prepared (Silburn et al. 2004, see Appendix 1) and distributed widely on CD's. 500 copies of the publication have been printed and distributed.

4. Achievements

Key achievements:

1. Achieved broad agreement in the cotton industry about Deep Drainage as a management issue in relation to the water balance at both field and catchment scale;
2. Identified key gaps and formulated recommendations for research during a workshop on groundwater and surface water interactions;
3. Communicated outcomes and published two chapters in the Cotton Industry's WATERpak Manual focusing on deep drainage measurement and review, and ensured that deep drainage was include in the Cotton Industry's Land and Water BMP module; and
4. Initiated and developed a new coordinated research program which covers landscape impacts of cotton irrigation on ground and surface water (Program 2 - The Catchment in the Cotton Catchment Communities CRC).

Achieved broad agreement

As a result of the presentations to and interactions with cotton growers, researchers and consultants, broad agreement has been reached that deep drainage does occur under irrigated cotton production, with measurements/estimates typically between 100 – 300 mm/year.

There is also agreement that deep drainage varies due to climate, soil type and management and that the range could be much wider. Field trials and modelling indicate there is considerable scope to control deep drainage and to improve water use efficiency by changing irrigation practices. It is also recognised that some deep drainage is beneficial under irrigation to flush out excess salts (the so-called leaching fraction). An adequate leaching fraction is probably provided by deep drainage during rainfall except where irrigation water is of high salinity. There is also some emerging evidence from the St. George area in Queensland that groundwater tables are rising due to cotton irrigation, evidence which is similar to that found much earlier in the Macquarie valley in NSW (Willis et al., 1997).

Figure 1 Animated discussion during the NMD - WBG workshop (Nov 2003) on groundwater and surface water interaction which was attended by 50 people representing 20 organisations.

Identified research gaps and recommendations

1. Spatial scaling

There is a clear need to have more focus on spatial scaling. Currently, several research projects, which collect measurements or estimates of deep drainage, are ongoing or have been completed. However many of the measurements are only representative for the research location, often a point, and cover only short temporal scales. A major question is how these local measurements translate to catchment scale and long-term predictions of impacts of deep drainage. This is not easy to estimate because catchments include different landuses and soil types. Given that some local deep drainage is beneficial, there is a need to identify the impact of the "minimum" amount of deep drainage on catchment targets for deep drainage and salt movement. At least two new funding proposals in the Cotton Catchment Community CRC (CCC CRC) focus on this aspect and suggest using simulation modelling approaches to identify how possible restrictions on catchment scale deep drainage impact the irrigation industry.

2. Vadose zone and interactions between groundwater and surface water

Estimates of deep drainage do not match up with estimates of groundwater recharge, both at the local and the catchment scale. This means that our understanding of what happens with deep drainage water once it passes below the rootzone is still very limited. This area, often called the vadose zone, is not very well researched (Fig. 2). The underlying shallow (and often saline) groundwater table is also less well researched and mapped than its deeper (productive) counterpart. This is because the vadose zone and the shallow groundwater table have been of limited interest to both crop (the water is lost) and groundwater managers (the water has not arrived or is not of any use). Except for a single detailed study in the Liverpool plains (Timms et al. 2001) there has been no research on this topic in the Northern Murray Darling Basin. Since this was identified as a significant gap, some recent work is being developed as part of CCC CRC project (Des McGarry) in Queensland. In addition, the work on ACCRC project 3.2.20 (Palaeochannels) around Moree and the shallow groundwater investigations in the Narrabri formation (DIPNR) west of the Newell Highway will collect valuable soils data. This will also assist in understanding the behaviour of the shallow groundwater system underlying much of this area.

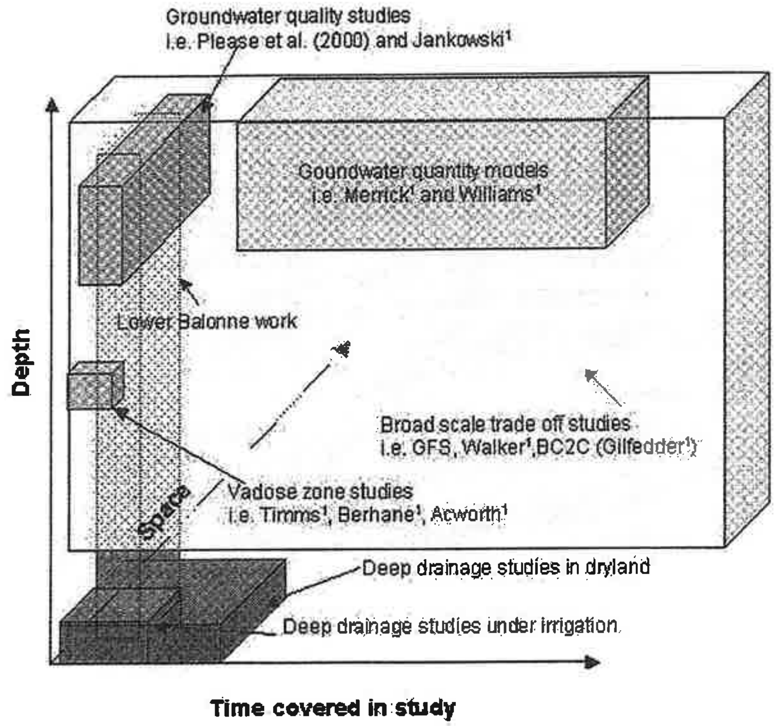

Figure 2. Overview of spatial and temporal coverage of current and completed studies on deep drainage and groundwater. As there is a trade-off in accuracy and detail with extend in space and time, this indicates a major gap in detailed studies in the vadose zone area and a gap in long-term detailed studies. For more detail and references mentioned see Silburn et al. (2004)

A related research gap is the interaction between surface water and groundwater in semi-arid areas and the location of recharge areas in the landscape. Earlier work by Triantafilis et al. (2003) has broadly identified areas of lighter soils and prior streams (palaeochannels) as areas of possible higher deep drainage and recharge. River channels and flood waters are also seen as a major source of recharge in some catchments according to groundwater modelling work by Williams et al. (1989). This work suggests that the recharge from these events and areas far outweighs the recharge from irrigated production. There is however little physical measurement or estimation of this process due to the spatial and temporal scales at which this process operates. Recent local estimates of deep drainage suggest a much greater contribution. In particular, the low frequency of bore and piezometer readings (2 – 4 times per year), a lack of monitoring in shallow aquifers and little knowledge of water movement through the unsaturated zone (discussed above) are major limitations. There is an urgent need for more frequent measurements at several locations to estimate the interaction between surface water and groundwater. Such measurements would also enable closing the "water accounting gap" suggested by Evans (2005). Further negotiations between the CMA's (stakeholders) and research providers should develop knowledge in this area. In addition, a funding proposal to program 2 in the new CCC CRC suggests looking at short temporal scale behaviour of groundwater levels and attempting to extract more useful information from existing data using advanced statistical techniques.

3. Measurement techniques

Measurement of deep drainage and recharge is still difficult, despite the development and documentation of a range of methods (for example the Zhang and Walker (ed.) 2002 series). Many of the existing methods have high uncertainties, with many of them better classified as estimates rather than measurements. This means that, apart from the labour and capital intensive lysimeter system, no single method is perfect. Considering that there is a trade-off between accuracy and cost (Fig. 3), it is important to validate different estimates. This is a task under current investigation by the Queensland Department of Natural Resources and Mines (NR&M) who have been collecting three concurrent measures of deep drainage over the past three-years. Direct measures of deep drainage from constant suction barrel lysimeters are compared to two indirect measures of deep drainage. One using annually collected soil chloride data for mass balance calculations via the model SODICS, the other using irrigation flow rate and advance data via the model SIRMOD, and deep drainage gained as the difference between infiltrated water and Et. The current CSIRO "large" lysimeter project funded by the CRDC, also aims to create a benchmark for other methods. In the same field, several different methods for estimating deep drainage are being compared to the lysimeter results, including three of the NR&M barrel lysimeters. Such "cross validation" allows calculation of uncertainty in the measurements and more confidence in research outcomes.

Apart from this benchmarking of existing methods, there is also a need for the development of new methods of measuring deep drainage or changes in soil moisture. This is particularly true for further development of methods that can estimate deep drainage at larger scales. There has been some development in using EM and geophysics to estimate deep drainage (Triantifilis et al. 2004, Cook and Williams, 2002) and movement of soil moisture (Drs. B. Kelly and I. Acworth), but these methods are still not fully developed and are only rough indications or estimates. Further development of the existing methods to improve accuracy, or development of totally new methods is still very much needed.

4. Knowledge and data management

A gap still exists in the management of knowledge and data. There is an urgent need to capture existing knowledge in a better way. This will prevent "reinventing the wheel" and improving the training of new specialists in the area. Knowledge management consists of two components: Data and dissemination. Databases and publicly available data are still scarce, or contain little information that meets research needs. Data generated by researchers is mostly reasonably inaccessible and remains in a "grey" form. It sits on researchers' hard drives or on compact discs stacked away as backups. Sometimes reports are written in which part of the data is supplied, but generally the focus is on the publication of research papers, which often only contain summaries of data, rather than the actual data. There are only a few examples in which researchers have attempted to make the data publicly and widely available. The most recent example is probably the Australian Cotton CRC Soils database (Odeh et al., 2004). A project proposed in program 2 in the CCC CRC is intended to collate water balance and deep drainage data from past and current studies in the cotton industry and make it available for testing models.

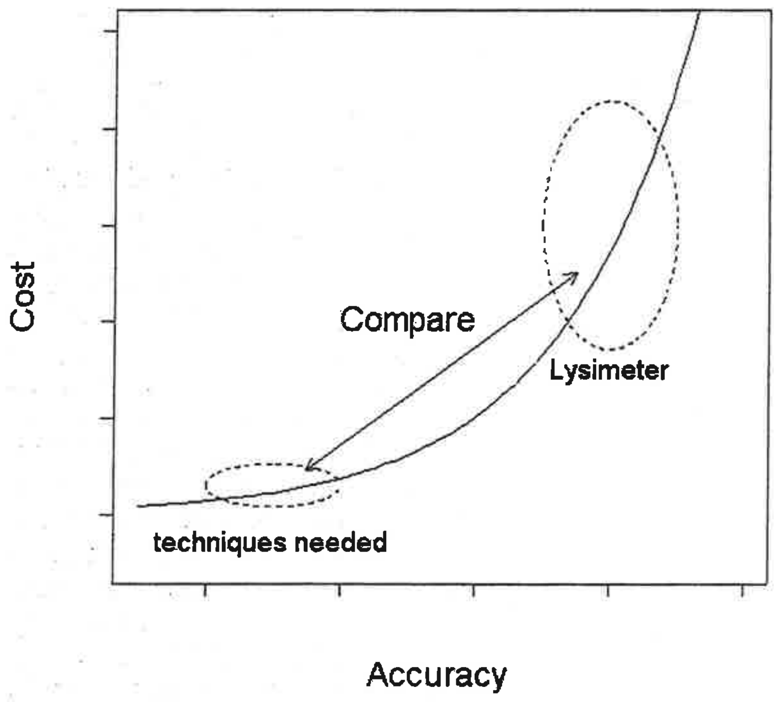

Figure 3. Schematic representation of trade-off in costs and accuracy for techniques for measuring and estimating deep drainage. Comparison of low cost - low accuracy methods with high cost - high accuray methods will increase confidence in the lower cost rapid assessment methods.

Developed coordinated research program

Through stakeholder meetings and workshops, the NMD – WBG effectively mapped the existing research on deep drainage in both dryland and irrigated agriculture. Based on identified gaps we set out to establish a range of connected research projects. The main project was based on the investment of the CRDC in a lysimeter facility at the Australian Cotton Research Institute at Narrabri. This was seen as the most accurate type of measurement and was needed to benchmark other estimates of deep drainage (i.e. Fig 2). In addition to this work, a series of other projects were identified and connected to the project. This "deep drainage under irrigated cotton" research program now includes:

1. The work on barrel lysimeters/Cl tracers/water balance (Dr. D. McGarry et al.) in NSW and Queensland, including the three barrel lysimeters recently installed in the field next to the CSIRO lysimeter (Fig. 4).
2. The electrical imaging work (Dr Acworth and Dr Kelly) to identify areas of high soil moisture and track water flow. Measurements of this type have been completed in fields containing barrel lysimeters and the main lysimeter.
3. The palaeochannel work (Dr. W. Vervoort and C. Vanags) to identify the extent of deep drainage in these features and management options. Electrical imaging work is planned for this site. There is also cooperation with DIPNR in the work to identify the behaviour and characteristics of the Narrabri formation. Piezometers have been installed at this site and similar piezometers are planned for the main lysimeter site.
4. Ongoing water balance estimations using chloride balance and water balance models in the cotton farming systems trials (T. Weaver and Dr. N. Hulugalle). The main lysimeter facility is located within the farming systems trial plots and thus allows cross validation of the results.
5. A CRDC project by E. Trainer/A.McBratney/B. Minasny (The University of Sydney) to develop a quick measurement of Deep Drainage potential was tested in the same field as the main lysimeter facility
6. Long stop and full stop drainage meters will be installed during the 2005-06 growing season adjacent to the main lysimeter at ACRI (Dr. R. Stirzaker)

Overall the lysimeter facility at ACRI has been developed into an active "field laboratory" site where different measurements of deep drainage are taking place.

The irrigated component has initially been linked to deep drainage investigations in dryland agriculture through informal relationships with NR&M, NSW DPI and DIPNR. However these informal relationships have allowed scoping of research issues during meetings and workshops and this has evolved into cooperation and investment into program 2 "the Catchment" in the new Cotton Catchment Communities CRC.

Within this new program, 10 research proposals in the area of deep drainage and groundwater surface water interactions are being considered. Many of the proposals focus on the catchment as a whole but use the information from the deep drainage under irrigation projects.

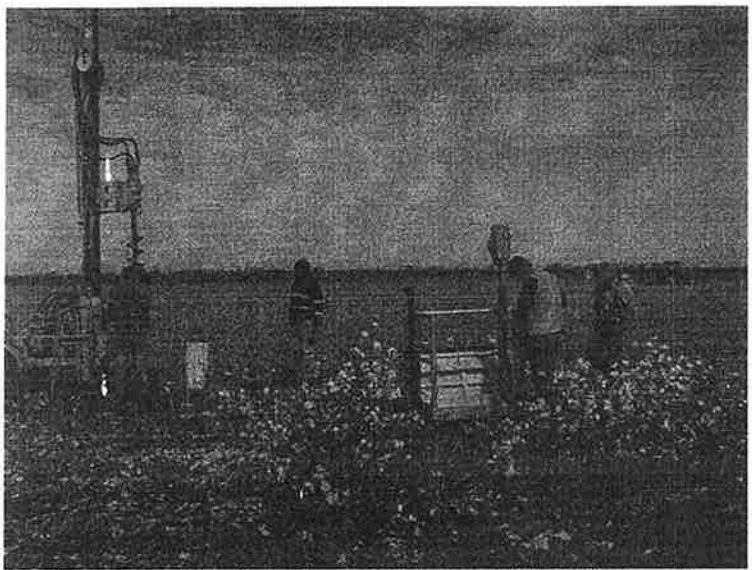

Figure 4 On the left - Grant Millar and (NR&M) installing one of the NR&M barrel lysimeters - close to (on the right) the large (shelve-type) CSIRO lysimeter at ACRI, Narrabri (May 2005). Picture courtesy of Dr. Des McGarry.

Des McGarry QNRM, Anthony Ringrose-Voase CSIRO and Lloyd Finlay NSW DPI preparing for the installation of mini lysimeters and other instrumentation. (Photo courtesy of Guy Roth)

Mark Silburn QNRM working on the GRDC funded lysimeter work that has formed linkages to the cotton work.

Ian Acworth UNSW and Bryce Kelly UTS testing electrical imaging techniques who have become part of the Cotton Deep drainage group as a result the improved coordination (Photo courtesy of Guy Roth).

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6. Funding

This project is greatful of the $50,000 received from LWA – National Program of Sustainable Irrigation to help facilitate the group activities, communication and travel. The Australian Cotton CRC, CRDC, NSW DPI, CSIRO Land and Water, QNRM, UTS, UNSW all contributed many hours of time and other resources to this project, which had an estimated value of $150,000.

7. Further Information

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Appendix 1 Knowledge Assets and Communicated Results

Refereed conference papers:

- Vervoort, R.W., Glendenning C. and Odeh, I.O.A. (2004). Development of deep drainage risk maps for the Border rivers area of NSW and Queensland. In: Singh B et al. Supersoil 2004: Program and Abstracts for the 3rd Australian New Zealand Soils Conference, University of Sydney, Australia, 5 – 9 December 2004. Published on CD and www.regional.org.au/au/asssi/

Reviews and Book Chapters:

- Two chapters on deep drainage were included in "WATERpak – a guide for irrigation management in cotton".
    - Ringrose-Voase, A. (2004) Water Balance and deep drainage under irrigated cotton pp 17-28.
    - Silburn, M. & Montgomery J. (2004) Deep drainage under irrigated cotton in Australia: a review pp 29-41. (These are in print as well as on the Cotton CRC website).
- Silburn, M., Vervoort R.W. and Schick, N. (2004) Deep drainage – so what? Part A & B. Report on 2nd NMD – WBG workshop, 19-20 November 2003, Narrabri. Cotton Research and Development Corporation. ISBN 1 87635498 4.

Conferences Presentations:

- Vervoort, R.W *et al* . (June 2005) A review of Deep Drainage and Water Balance Work. Annual Cotton CRC Review (attended by 150 scientists, research managers and some growers).

Seminars, Workshops & Trade Shows:

- Vervoort R.W. (2004) Outcomes of the Deep Drainage Workshop–2003 Annual General Meeting of the Irrigation Association of Australia North West
- Vervoort, R.W and Silburn M. (June 2004) Water Balance – progress and outlook. Australian Cotton CRC 5th year Review, Narrabri, NSW.

Grower Magazines and Articles:

- Triantafilis, J. Odeh, I. Short, M. (2004) Identifying deep drainage risk areas in the lower Gwydir, The Australian Cotton Grower Feb – March pp 19-22.
- Triantafilis, J. Buchanan, S. Short, M. Malik, R. (2004) Mapping subsurface saline material at Bourke, The Australian Cotton grower pp Feb March 59-61
- Hood, S. Hulme, P. Harden, B. Weaver T. (2004) Methods for measuring deep drainage. The Australian Cotton grower Dec-Jan pp 28-31

Media Release

- Deep Drainage Studies to Improve Cotton Water Management, June 2005
- Concerned Growers Cotton On, May 2005
- Major Deep Drainage Forum in Narrabri, Nov 2003

Other:

Tim Lester of Land and Water Australia used the report as a background to a one page glossy flyer of the project – which was one of two projects LWA promoted at the 12th Annual Cotton Conference attended by 1400 delegates.

Appendix 2 - MEDIA RELEASE

DEEP DRAINAGE STUDIES TO IMPROVE COTTON WATER MANAGEMENT

A major study measuring deep drainage under irrigated cotton in the northern Murray Darling Basin could have important implications for water use efficiency and management in the cotton industry.

The Cotton CRC project now involves collaboration between CSIRO Land and Water in Canberra and Narrabri, the NSW Department of Primary Industries and Queensland Natural Resources and Mines.

By utilising equipment and techniques developed by the project team, cotton irrigators will better comprehend and understand the fate of irrigation water during application, and ultimately be able to improve irrigation practices to minimise drainage.

The focus on drainage has increased because of concerns about both the efficiency with which irrigation water is used and about environmental damage caused by excess drainage through waterlogging, salinity and the movement of agrochemicals into waterways.

Previous work on drainage has either used indirect measurements based on calculation of fluxes from the soil water profile measurements, chloride mass balance, or modelling to estimate its magnitude.

This current Cotton CRC project at ACRI Narrabri attempts to directly measure drainage under an irrigated cotton system using an equilibrium tension drainage lysimeter comprising six trays installed at 2 m depth which collect drainage over 1.5 square metres, installed via a horizontal tunnel projecting from the side of a 2 m diameter × 4 m deep concrete access shaft.

In addition to the collection trays, the facility includes two vertical arrays of tensiometers; one of 'Echo probes'; four neutron probe access tubes and a weather station. A siphon meter and wetting front detectors will be used to measure the amount of irrigation water entering furrows above the lysimeter.

The lysimeter facility has three objectives.

- The first is to measure drainage and better understand when it occurs during the crop rotation.
- The second is to act as a benchmark against which to test other, less expensive methods of measuring or estimating drainage, which can be used in many more locations.
- Finally, data from the facility will be used to improve water balance models that can be used in conjunction with farming systems models to estimate drainage at a range of locations over long time periods (decades) and under a range of management systems. Such models can then be used to design more efficient and environmentally benign irrigation systems.

The Narrabri study is complementary to a similar project in Queensland funded by the Queensland Government and backed by the Australian cotton industry, the Cotton Research and Development Corporation (CRDC), and the Cotton CRC.

Seven growers around Pittsworth, Dalby, Goondiwindi, Dirranbandi and St George are working closely with Queensland's Department of Natural Resources and Mines (NR&M) to monitor deep drainage that wastes water, and which can contribute to rising water tables and salinity problems.

With these recent installations, there is now more than 25 barrel lysimeters under cotton fields across southern Queensland and northern New South Wales, placing the Australian cotton industry at the global forefront of deep drainage research.

CRC personnel involved in this deep drainage research project include Dr Anthony Ringrose-Voase, CSIRO Land and Water, Canberra, Tony Nadelko, CSIRO Land and Water, Narrabri, Dr Nilantha Hulugalle, NSW DPI, Narrabri and Dr Mac Kirby, CSIRO Land and Water, Canberra, Dr Des McGarry NR&M and Dr Thusitha Gunawardena, NR&M. The collaboration is being supported by the National Program for Sustainable Irrigation.

Further information: Dr Des McGarry, NR&M 07 3896 9566, Dr Anthony Ringrose Voase CSIRO 02 6246 5956, Dr Nilantha Hulugalle NSW DPI 02 6799 1500.
June 5 2005

Appendix 3 - Research Updates and Technical meetings.

Date	Meeting	Detail
26 – 27/11/03	CRDC & Cotton CRC Farming Systems Forum	Presentation of outcomes from the Northern Murray-Darling Water Balance Workshop 2 "Deep Drainage – so What?"
15/12/03	Meeting with Mick O'Fynn EPA, NSW – Sydney	Outcomes and gaps of the workshop formed some of the basis for an EOI for a large integrated program - Integrated Environmental Program – Environmental Trust

15/12/03	Meeting with WWF – International cotton water program Sydney	Outcomes and gaps from workshop were discussed in relation to future collaborative efforts – commitment to partner in a water project pending Cotton CRC's rebid success
5/02/04	Meeting at UNE with CSIRO SE, DEC, USYD, DIPNR, UQ	Discussing future collaborations with regard to Cotton Environmental gaps from soil/ water gaps through to links to terrestrial biodiversity. If any biodiversity study is to be done there needs to be a good understanding of the connection to DD and Groundwater quality.
9/02/04	Large Technical meeting of research providers CRCIF, CRCFE, UTS, UNSW, USYD, NSW AG, QDNR, DIPNR, CSIRO L & W, CSIRO SE.	Meeting to discuss commitment to future integrated water research including Deep Drainage and its interaction with Ground water and surface water and risks associated. – both environmental and production related
19/02/04	Cotton CRC workshop for commercial partners	Gaps and outcomes of the workshop were discussed in light of future collaborative opportunities and resource possibilities
24/02/04	CSIRO L&W and indirectly CRCCH - Canberra	Gaps and outcomes of the workshop were discussed in light of future collaborative opportunities
24/02/04	CRCFE - Canberra	Gaps and outcomes of the workshop were discussed in light of future collaborative opportunities
18/03/04	NW NSW IAA – AGM - Narrabri	Willem Vervoort Presented a Summary of the Workshop outcomes as a guest speaker.
29/03/04	Condamine Alliance - Toowoomba	Gaps and outcomes of the workshop were discussed in light of future collaborative opportunities – Subsequently put forward a written submission on their Blue Print outlining the gaps and outcomes of the workshop that need to be incorporated. Since then they have been.
8/04/04	Pratt Water - Gunnedah	Gaps and outcomes of the workshop were discussed in light of future collaborative opportunities
04/04	Namoi CMA - Gunnedah	Gaps and outcomes of the workshop were discussed in light of future collaborative opportunities
20/04/04	CSIRO L&W, CRDC, NSW AG, QDNR - Narrabri	Meeting to finalise placement details and measurements to be taken from Lysimeter to be installed at ACRI Narrabri
6-7/05/04	MDBC – Committee - Narrabri	John Triantafillis presented the Gaps and outcomes of the workshop which were discussed in light of future collaborative opportunities
18/05/04	Namoi CMA Board Meeting - Tamworth	A presentation was made including gaps and outcomes of the workshop and discussions were had in light of future collaborative opportunities
21/05/04	CW CMA – Dubbo	Gaps and outcomes of the workshop were discussed in light of future collaborative opportunities
	DIPNR Northern NSW Technical Workshop - Tamworth	Presentation made including Gaps and outcomes of the workshop
25/08/04	CRCIF & CRCE Water	Gaps and outcomes of the workshop were discussed in light of future collaborative opportunities
22/09/04	CRCIF Workshop Deep Drainage – Sydney	Gaps and outcomes of the workshop were discussed

25-26/10/04	Science in Parliament - Sydney	John Triantafillis & Sam Buchannan Hosted a stand outlining among other water soil issues – the importance of addressing the Gaps and outcomes of the workshop
26/10/04	UTS & UNSW – Narrabri	Further discussions into the detail of future collaborations aimed at addressing the gaps and outcomes of the workshop
16/11/04	Northern MDB Freshwater Forum – Goondiwindi	Presentation made including Gaps and outcomes of the workshop
16/12/ 2004	CRDC, QNRM, Cotton CRC, Usyd, NPSI, Aquatech Consulting.	Face to Face meeting in Narrabri – Lysimeter Research Science Panel - Measuring and Assessing the Risk of excessive Irrigation induced Deep Drainage – Minutes distributed to all participants. Email follow up – collaborative opportunities – potential funds leverage source – Cotton Catchment Communities Ongoing correspondence with all researchers.
15/ 04 / 2005	Various organisations	Expressions of Interest (EOI) due to CCC CRC – 28 EOI's that were submitted fell in the area of Deep Drainage and the interaction with Groundwater.
21/04/ 2005	Face to Face meeting in Narrabri - Groundwater and Groundwater-Surface Water Connectivity	Face to Face meeting in Narrabri - Groundwater and Groundwater-Surface Water Connectivity researchers (potential new sub-program CCC CRC) Minutes distributed to all participants.
5/ 05/2005	Various organsiations	10 Full applications were received by the CCC CRC
19 /05 / 2005	Phone hook up of all the various organisations.	Phone Hook up to discuss further collaboration and coordination of full applications for consideration of the CCC CRC
1 - 2 / 09 / 2005	Technical meeting of deep drainage group in Sydney of peak stakeholders.	About 27 people attended from various organisations. Future projects were refined.

Appendix 4 - Key Meetings with Catchment Authorities In NSW and Regional Bodies in Qld

Dates	CMA	Details
8th March 2005 1st April 2005 26 July 2005 1st September 2005	Namoi CMA	The Namoi CMA agreed that deep drainage is important and they have agreed to fund a Water Use Efficiency officer at Gunnedah for 3 years. The CMA management advised that they had applied for a large project on drainage using multiple pieziometer sites over a catchment that if this were to be successful there would be much opportunity for value adding with new projects.
3rd Aug 2004 13th Sept 2004 5th August 2005 17th October 2005	Gwydir / Border Rivers CMA	Since the new CMA board was appointed we have had much correspondence discussing areas of research collaboration. Follow up email, phone conversations and further correspondence (4th June 2005) has not yet provided a position regarding investment into water balance / deep drainage work with the Gwydir. However, there has been a commitment to further discuss collaboration. More recent meetings 5th August, 17th October have lead to potential funding of a water use efficiency officer to extend deep drainage information in the Gwydir Catchment/

March 2005	Central West CMA	As a result of two meetings with the new chairperson and general manager there is an indication of interest and discussions are continuing.
12th May 2005 31st May 2005 29 August 2005 30th September 2005	Condamine Alliance	After many discussions and meetings the Condamine Alliance agreed to fund extension related activities to improve water use efficiency and water balance calculations/ improved grower awareness. They regret that they are not in a position to fund research per se although they recognize the importance of deep drainage and its consequences and therefore will investment in extension activities.
Date 31st May 2005 1st Sept 2005 30th Sept 2005	Queensland Murray Darling Committee	QMDC visits. Met and discussed collaboration resulting in submitting proposals for their consideration. Some financial commitment is likely to deep drainage work of McGarry/Silburn et al.

Report on
Northern Murray-Darling Water Balance Workshop 2.

'Deep drainage – so what?'

'Where is it going and what is it going to do and when?'

Narrabri, 19 – 20 November 2003

Silburn DM, Vervoort RW, Schick N

for the

Northern Murray-Darling Water Balance Group
2004

Members of the Northern Murray-Darling Water Balance Group, under the auspices of the Australian Cotton Cooperative Research Centre:

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A – Australian Cotton CRC
B – CRC Catchment Hydrology

The purpose of the NMD Water Balance Group is to foster understanding and sound management of water in northern NSW and southern Queensland, by providing coordination and education in the science of water balance.

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The notes on main points from the presentations and discussion were prepared with typical thoroughness by Willem Vervoort. Written submissions were not refereed and are entirely the work of the authors. Anthony Ringrose-Voase and Nilantha Hulugalle provided valuable editorial comments. Publishing assistance was provided by Elizabeth Tout of CRDC and David Larsen, Technology Resource Centre, Cotton CRC

We appreciate the efforts of the people who 'volunteered' to co-chair sessions, who kept things organised and on time (mostly), and particularly, to chair sessions, which included giving an opening address - Anthony Ringrose-Voase, Ted Gardner, Glen Walker, Mac Kirby, Michele Akeroyd (see Section 8). Chris Vanags and Dianne Bennett (University of Sydney) assisted with the smooth operation of the workshop. The Narrabri Golf Club provided an excellent venue and food for the dinner.

The workshop was supported by Australian Cotton Cooperative Research Centre and funded in part by National Program for Sustainable Irrigation, Land and Water Australia, under project 'CRD2 - Coordinating Deep Drainage Research'.

Table of Contents

1 Summary report on the workshop

By Mark Silburn

The workshop was intended to consider deep drainage (movement of water below the root zone of plants) from all major land uses in the northern Murray-Darling Basin (MDB). Though held in Narrabri, it was not an 'irrigation' workshop! In particular, we wanted to consider the **consequences of deep drainage,** and associated salt leaching, to groundwater and rivers. This involved bring together 'surface/soil', 'groundwater' and 'river' scientists, who have tended to work independently in the past.

To set the scene, recent studies of deep drainage under dryland (Session 1) and irrigated cropping in Queensland, NSW and Victoria (Session 2) were presented, summarising progress since the previous workshop (CRDC and ACCRC 1999). Since that workshop, deep drainage was recognised to occur on the clay soils dominantly used for agriculture in the northern MDB. This was reinforced by recent studies. It was notable that confidence in measuring and modelling deep drainage has increased considerably since the last workshop. Under dryland cropping, drainage rates are generally a small proportion of rainfall, but are still more than an order of magnitude greater than the low rates observed under native vegetation. Under irrigation, drainage rates are typically greater again. However, under both dryland and irrigated cropping, drainage was highly episodic and varies considerably depending on rainfall/irrigation, soil properties and features of the cropping system.

Deep drainage in itself is not necessarily a problem. It can be a resource, by recharging groundwater, an important source of water supply in the northern MDB (e.g. Williams[1]). Some drainage, or leaching fraction, is required when irrigation water contains salts, to prevent salts accumulating in the soil. However, experience in southern Australia shows that the increase in deep drainage after replacement of native vegetation with cropping, and particularly irrigation, can lead to rising groundwater, causing increased land salinisation and salt loads in streams.

Catchment water balances in the Northern MDB (e.g. MDBC 'Tributaries' project, Beecham[1]) indicate that baseflow (low flows sourced from groundwater) is often a small component of streamflow. This reflects groundwater levels below streambed levels (Pearce[1]) and low recharge rates during the historical response times of groundwater systems (e.g. 10's to 1000's years). Also, many streams lose water when they flow across the riverine plains. This water may be recharging groundwater (Jankowski[1], Merrick[1]), or simply be absorbed into the soils and be transpired. Catchment salt balances in the Northern MDB (Walker[1]) indicate a historical net accumulation of salts (from rainfall). Accordingly, the soils, regolith and some groundwater in the region often contain considerable salt. There is no shortage of salt in the landscape to let us off the hook!

It is a gross oversimplification to assume that these processes occur uniformly across the Northern MDB. It was notable at the workshop that parts of the region have contrasting behaviour or are at different stages along the response curve (groundwater response to increased recharge, Walker[1]). Being overly general leads to discussion at cross-purposes.

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[1] Refers to papers, presentations and comments during discussion at the workshop.

The final element in the drama is the groundwater systems. Definition and mapping of a consistent set of groundwater flow system classes (GFS; Walker[1], Williams[1], Pearce[1]) assists interpretation of potential response to recharge, though the specific properties of each GFS are no necessarily well defined. Drilling in the Qld MDB over recent years, in areas not used for water production, indicates a wide range in depths to groundwater (5-50m), often with moderate to high salinity (Pearce[1]). Little trend data are available as yet. Some mounding of groundwater has been noted under irrigated areas (Free at al. 2001). In contrast, in areas used for water production (pumping), water levels are generally falling and salinity level may well be rising (Williams[1], Jankowski[1]). Regional scale GFS (e.g. Upper and Lower Namoi, Lower Balonne) have multi-layered aquifers and interpretation of response to recharge is complex.

The consequences of deep drainage are distinctly different where underlying groundwater is used for pumping (fresh water, high flow rate) and where it cannot (saline water or low flow rate). Fresh groundwater resources are widely developed for irrigation and domestic water supply and there are concerns that they are, or may be, overused (Williams[1], Merrick[1]). In this case an increase in recharge via deep drainage can be seen as a good thing. However, this is often associated with downward movement of a large mass of salt (Silburn[1]) and the groundwater may become more saline. Rates of water and salt movement in the unsaturated zone are poorly defined and may involve rapid (preferential) and slow (matrix) components (Timms[1], Acworth[1]). Time lags between drainage occurring and groundwater recharge are thus uncertain, but vary widely in different materials. They may be large (decades), particularly where native vegetation has left a large water deficit in the unsaturated zone.

Studies in the Lower Namoi (Merrick[1], Jankowski[1]) highlighted an apparent disparity between deep drainage rates measured in the soil and the lower recharge rates interpreted from groundwater data and modelling. However, a more formal analysis should be conducted before this is accepted as 'fact'. This requires an analysis of the volumes of drainage water from **all** land units/uses overlying the groundwater system and consideration of, for example, the area actually irrigated each year, the time-lags in the unsaturated zone, and the role of palæochannels in intercepting drainage and routing it laterally. At least some of the soils in the Namoi have lower deep drainage rates than other irrigated soil (Silburn and Montgomery 2004). Once the area (and years) irrigated is combined with other land uses, the average drainage rate contributing to the groundwater system might be reasonably small. Comparison is hampered by the use of units of volume (e.g. ML) in groundwater models and depth (mm) in surface water balances.

This reminds us that the consequences of deep drainage and development of salinity is a whole of catchment issue, or at least whole of groundwater 'catchment' issue. Groundwater systems generally underlie large areas. Even 'local' GFS are considered to be up to 5 km in extent. Thus groundwater systems receive recharge from a multitude of land types, land uses, and may lose and gain water from the stream network. Vervoort *et al.* (2003) estimated deep drainage contributions in the Namoi catchment of roughly one third each from irrigated, dryland cropping and grazing lands (for 3%, 20% and 60% of catchment area, respectively).

The Lower Balonne study (Wilkinson[1], Fitzpatrick[1], Claridge[1], Pearce[1]) is a good example of an integrated study, in this case of a large regional GFS, although the difficulties and cost were acknowledged. This included studies of geophysics (airborne, ground and downhole), hydrogeology, soils, geomorphology and geochemistry. Results include a groundwater conceptual model and monitoring network, salt store and soil attribute mapping. A further stage is required to determine the response of the system (water and salt balances) to land use. Buchanan[1] is conducting a similarly integrated study on a finer scale at Bourke.

Ultimately, the consequences of deep drainage will only be determined by using some form of integrated surface-groundwater models. Gilfedder[1] outlined orders of modelling from simple (prioritisation, planning tools), such as BC2C (Dowling *et al.* 2003) and Salinity Hazard Mapping (Claridge[1]), to complex numerical models. The spatial prioritisation tools are based on simple conceptual principles and are configured to use only that information which is available readily and spatially (Akeroyd[1]). Several studies have recently evaluated methods for generating one of the required inputs, i.e. deep drainage maps over the extent of the groundwater system (Claridge[1], Vervoort[1]). These combine soil and land use mapping with water balance modelling (see Silburn and Owens paper[1]). They provide one option for moving from hazard assessment and to risk assessment as they include effects of land use on drainage (Biggs and Brough 2002). The level of detail in such drainage maps greatly outweighs the knowledge of properties of the hydrogeology. However, the apparent level of detail should not be seen as a problem – it's just easier to estimate drainage 'soil-by-soil' and aggregate up, than it is to estimate a 'lumped' average value. Scarcity of data for hydraulic properties is something the soil and groundwater sciences have in common.

I am conscious that a summary of the workshop would be different from a groundwater scientist's perspective. Over use (depletion) of our valuable fresh groundwater resources is obviously a major concern, even though this report is mainly from a salinity perspective. From my position of ignorance, I imagine that groundwater modelling has mostly involved aquifer systems where pumping is occurring. I wonder if the difficulties involved (e.g. getting a useful calibration) are less, or different, in modelling systems with little pumping, basically just filling up after a change in recharge.

One thing that has not changed since the last workshop is that few studies where drainage is measured (at considerable expense) are modelled in detail. This is an essential step in providing confidence in the models and deriving their parameters, and often provides greater insights about the measured data. Of all the measurement studies of drainage under irrigation reviewed by Silburn and Montgomery (2004) up to about 2001, and since (Raine[1] and Dalton, Wiggington, McGarry[1], Weaver[1] and Hulugalle[1]), **none** that I know of have been used in water balance models. This is a surprising loss of value adding! The situation is somewhat better for dryland agriculture, where 'measurers' and modellers have been 'interbreeding' for several decades.

The first NMDB water balance workshop ended in considerable confusion (deep drainage in clay soils – what?), which stimulated people to think through the issues, and resolved within a year into a much more considered view of the situation. The notes on the discussions at this workshop (dutifully recorded by Willem) give some interesting insights. Further information on some topics is provided in the submitted papers (Part B). It is obvious that our science is now under public scrutiny (Harris[1], Finney[1]). The second workshop ended in a somewhat similar way to the first, with no great consensus or neat-and-tidy grand 'outcomes', which I hope bodes well for some critical thinking and integration of ideas.

2 Overview of the workshop

2.1 *Background*

The 'Cotton Industry Water Balance Workshop' was held in Toowoomba almost four years ago (CRDC and ACCRC 1999). That workshop revealed confusion about deep drainage and water balance for irrigated clay soils. Available data (e.g. Thorburn *et al.* 1990, Willis and Black 1996) appeared to conflict with the long held view the 'clay soils don't drain' (e.g. Hearn 1998). This got people thinking and evolved fairly quickly to a consensus that considerable drainage was possible. Since then, understanding of soil water balance issues in the northern cropping areas has advanced, in both irrigated (e.g. Zischke and Gordon 2000, Gordon 2001, Moss *et al.* 2001, McHugh *et al.* 2002, Silburn and Montgomery 2001, 2004; Vervoort and Silburn 2002, Vervoort *et al.* 2003, Weaver *et al.* 2002 & this report) and dryland agriculture (e.g. Ringrose-Voase *et al.* 2003, Bell 2001, Tolmie and Silburn 2002, Yee Yet and Silburn 2002). In particular, there is a greater appreciation of rates of drainage below the root zone in these systems, and to a much lesser extent, how to model it.

This progress stemmed from a miscellany of projects, prior to and since the Toowoomba workshop. More recently these include (a) several large research projects focused on deep drainage under dryland cropping in southern Queensland (Bell[1], Silburn[1]) and northern NSW (Young[1]), through GRDC and state government funding, (b) a series of short term studies of deep drainage under irrigation in northern NSW, southern and central Qld, funded by CRDC, the Australian Cotton CRC and state government water use efficiency programs. One outcome is the development of lysimeters to accurately measure deep drainage. Several are in use/under construction under dryland cropping (e.g. Darling Downs, South Burnett and the Liverpool Plains, NSW) and one will be built under irrigated cotton in Narrabri, using CRDC funding. These lysimeters will be used to benchmark other deep drainage estimates, since there is still uncertainty about the accuracy of some of the methods and models to predict deep drainage. In addition, the Australian Cotton CRC has funded a project to look at the hydrology of prior streams and how these affect deep drainage and landscape water movement, and the CRDC has funded a project to look at effects of irrigation water quality on deep drainage.

Simultaneously, there have been advances in understanding salinity, more or less from the opposite end of the scale, involving various forms of statewide or catchment-wide spatial analysis. These include salinity hazard assessment (Gordon *et al.* 2002), now being carried through to risk assessment (e.g. Biggs and Brough 2002), and prioritisation for management of river salinity (Dowling *et al.* 2003). Groundwater is incorporated using mapping of groundwater flow systems (GFS) based on consistent catchment classification (Coram *et al.* 2000), though they represent only a first approximation due to the lack of data on shallow groundwater. The Catchment Classification case studies (NLWRA[2], MDBC) describe how some 'real' GFS behave from a salinity perspective (see for example, Cresswell *et al.* 2003). Historic salt loads and trends in the MDB streams have been analysed (DNR 2000, Jolly *et al.* 2001) and are currently being updated and modelled through the entire MDB stream network (MDBC 'tributaries' projects in Qld, NSW and Victoria). Both the spatial salinity risk assessment and river salt load modelling need to incorporate the impacts of land use change

[2] NLWRA – National Land and Water Resources Audit

on deep drainage and groundwater response. Therefore they depend on the 'fine scale' deep drainage studies discussed above, or more likely on models developed from these data.

A major concern is that shallow groundwater systems (e.g. <50m deep) will rise under higher drainage rates and begin to discharge saline water at the land surface and into rivers, as has occurred in other parts of Australia. Aside from anything else, this would have major consequences for the quality of water available for irrigation and domestic water in the northern MDB. That is, there are large productive assets at stake.

The 'missing links' between deep drainage change (due to land use change) and land and stream salinity are the unsaturated (vadose) zone and groundwater systems. Monitoring networks are sparse and are concentrated in pumped aquifers (for water management purposes). Aquifers used for extensive groundwater pumping often have declining water levels, for example the Lockyer, Condamine and Callide alluvia in Queensland (Gordon 2000) and the Lower Namoi in NSW (Williams[1], Merrick[1]). In contrast, rising groundwater (or mounding) has been observed in some non-pumped areas under irrigation, for example in the Border rivers alluvia (Free *et al.* 2001) and the Emerald irrigation area. A monitoring network to assess salinity has only recently been established in the Qld MDB (Ed Power, NR&M, pers. comm.). Drilling data have been compiled into a groundwater conceptual model for the Lower Balonne floodplain (Bruce Pearce[1]). This is part of an integrated study of soils, salinity and groundwater on part of the floodplain (Wilkinson[1] & Claridge[1]).

2.2 *The workshop*

Given that we know more about deep drainage, we are left with the questions: **Deep drainage – so what? Where is it going and what is it going to do and when?** The need to link on-farm management with catchment/river responses requires much **greater interaction within and between 'surface/soil', 'groundwater' and 'river' scientists**. While there have been advances in understanding deep drainage, there have also been advances in knowledge of groundwater systems, landscape and river hydrology and salinity in the region. But there are few venues for all of the people involved to share this new knowledge. This workshop was intended to facilitate communication between the scientists working on these issues, share some of the tricks of the trade and reflect on the as yet unanswered questions.

The workshop was organised by the Northern Murray-Darling Water Balance Group, a group of scientists from various organisations under auspices of the Australian Cotton CRC. Over the last three years, this group has worked to coordinate, integrate and communicate water balance research in the Northern Murray-Darling Basin.

While the workshop was held in the heart of the irrigated area at Narrabri, the breadth and width of the topics and submitted papers cover much more. In fact, it covers water balance issues in dryland as well as irrigated production and projects ranging from in-field to river basin scale, from local to regional groundwater systems. The workshop started by summarising progress in deep drainage knowledge since the last workshop and then expanded downwards into the ground and outwards across river systems.

The workshop had a clear technical focus, mostly relating to deep drainage, but was aimed at a broader audience than irrigated cotton production. Around 60 people from state and federal agencies (MDBC, CSIRO L&W, DIPNR, NSW Agriculture, Queensland Dept. NR&M and

DPI, and Victoria DPI), universities (The University of Sydney, UTS, UNSW, USQ & UNE), representatives of funding bodies and several catchment management organisations attended the two-day workshop. Expertise included soil scientists, hydrologists, hydrogeologists, geophysicists, agronomists, extension specialists, spatial and GIS experts.

Participants were invited to supply written submissions (papers) on a voluntary basis. This interesting collection of papers is published in Part B of this report (to reduce PDF file sizes).

2.3 *Program outline*

The program was set-up to leave ample time for discussion. The following topics were discussed during the workshop:

1. Deep drainage and the soil water balance under dryland cropping
2. Deep drainage and the soil water balance under irrigated cropping
3. Where have the water and salt gone and what is it doing? Regional groundwater stories
4. Integrating the story: the Lower Balonne case study
5. Where is the water and salt coming out? Rivers and landscapes
6. Final discussion and way forward

3 What we have learned

3.1 *Characteristics of the NMDB*

Direct measurements of deep drainage and complete water balance studies traditionally have concentrated on the uplands areas and Southern Murray-Darling Basin where the occurrence of salinity through deep drainage is perceived as a more pressing issue. Measurements from these areas are not readily transferable to the Northern Murray-Darling Basin due to the extensive areas of heavy clay soils (Vertosols), climatic (summer rain versus winter rain), and consequent differences in agricultural systems. Vertosols tend to have high plant available water capacities in which to store large amounts for rainfall. Agricultural development has occurred more recently in most of the region than in southern areas.

3.2 *Data and observations of components of the soil water balance*

From observations and measurements of the soil water balance at the workshop a few points are clear:

- Deep drainage occurs under all land-uses at various times
- Deep drainage under irrigated production ranges between approx. 50 – 300 mm/year
- Deep drainage under dryland cropping is considerably lower than under irrigation, but still larger than under native vegetation and is moving large masses of salts downwards in the soil
- Deep drainage and water balance components are episodic, irregular in time, spatially variable, and depend on soil, management and climate

➢ Results presented in this workshop should be included in the CRDC's WATERpak or one of its updates. Regular updating of water balance studies is important since new information is available every year (**Recommendation**).

A number of studies have been completed or are on-going to measure components of the water balance or deep drainage. However, given the large area of the Northern Murray-Darling Basin, the geographical distribution is still very small, and most studies are of short duration (1-5 years). Most of these studies are therefore more useful for process understanding or management comparisons, rather than absolute measurement.

In addition, it emerges from presentations by Ringrose-Voase and Vervoort, that the water balance components and deep drainage are highly episodic and variable. This has consequences in terms of measurements and projects that are generally in this area. As projects span only 1–5 years, these projects only sample a small part of the deep drainage distribution. Extrapolation using water balance models would add considerable value to these short-term measurement studies.

Main points from the observation section:

1. Deep drainage and other water balance components are being measured more widely
2. Spatial and temporal coverage is still very low
3. Comparisons of management and process understanding is possible, assessment of absolute values is less likely
4. Thus, extrapolation in time and space of 'reasonable' estimates is needed

Data presented by Silburn indicate that, in the NMDB, many (but not all) soils under native vegetation contain large masses of salts while under dryland cropping soils have lost reasonably large masses of salts in the time since clearing. The mass of salts lost per ha is larger than the mass typically exported in stream flow (DNR 2000, Jolly *et al.* 2001). Thus considerable salt has move down in soil profiles and is stored somewhere in the unsaturated zone and/or groundwater and is not yet being exported in streamflow.

3.3 *Methods and uncertainty*

3.3.1 Measurements

One of the key issues in the first workshop in Toowoomba was the accurate measurement of evapotranspiration. During the workshop it seemed that measurement of evapotranspiration using the Bowen ratio method is now accepted and common, with at least three projects using this method[3].

Measurement of deep drainage was also more common and a range of methods is being used. These methods were reviewed extensively in such papers as Scanlon *et al.* (2002) and Walker *et al.* (2002). Although researchers are using different methods, there was consensus about the accuracy of the different methods and their value considering limitations in cost, time and scale of measurement. Most of this consensus agrees with the discussion in the two mentioned papers. Many researchers also use different methods at the same location, for example McGarry[1], Montgomery[1] and Weaver and Hulugalle[1]. The different methods average drainage over different areas/scales (e.g. water balance of a field versus a point(s)) or time scales (event, season, decades), and may not be directly comparable. Silburn and Owens (submitted paper[1]) discuss limitations and suitability of various methods. However there is still a lack of quantification of the uncertainties related to the methods. Part of this uncertainty is related to spatial variability.

- ➢ Including uncertainties of measurement with all studies would improve cross-comparison of work (**Recommendation**)

Main points from the methods and uncertainty section:
1. There is general agreement on the accuracy and usefulness of different drainage measurement techniques
2. Uncertainty of measurement techniques is not widely assessed

3.3.2 Simulation models

Simulation models are useful to bridge the gap between limited measurements and the need for information in space and time. A range of different simulation models and algorithms exists (i.e. Walker *et al.* 2002). There has been considerable testing of soil water balance models against hydrologic data in the Northern MDB and related areas (e.g. Littleboy *et al.* 1992, Ringrose-Voase *et al.* 2003, Owens *et al.* 2003 to name a few). This has mostly been for dryland systems, with Connolly *et al.* (2001) being an exception. However, until recently there was little data for testing the drainage calculations in these models. Such testing is beginning now that data are becoming available (e.g. Owens *et al.* 2004). Few, if any, studies of drainage under irrigation in the Northern MDB have been modeled. Because so few

[3] A workshop on the Bowen ratio method is to be held in Tamworth in mid-2004.

reliable field measurements of deep drainage exist (or are available as complete, digital data), it is difficult to assess the reliability of the simulation outcomes.

- A concerted effort is needed to capture data from water balance measurement studies and use it to validate and parametise the models that will ultimately be used to extrapolate results. (**Recommendation**)

Similar to measurements of deep drainage, very few modeling studies include estimates of uncertainty. Presentation of data in a probabilistic or stochastic manner may improve interpretation of the outcomes. Many model frameworks are however not adapted to this type of modeling, the large numbers of simulations and management of large amounts of output files and data.

- Including modules in models to give statistical summaries of the output would improve estimation of uncertainties. (**Recommendation**) However, inclusion of such features will demand additional computing power.

Main points from the methods and uncertainty section:

1. Many models exists at the smaller (agronomic) soil water balance scale
2. Few studies quantify uncertainty of the outcomes and model frameworks are not well adapted to deal with probabilistic approaches
3. The accuracy of the models is difficult to assess due to the lack of field measurements, or lack of testing where data do exist

3.4 *Landscapes and integration*

At broad scales there are limited measurements and few mechanistic approaches to simulating water quality and quantity. The work by Timms and Berhane[1] is probably an exception. This work is trying to identify the properties and mechanisms of the vadose zone (between the root zone and the groundwater table). Water quality work in groundwater in the NMDB has mainly concentrated on broad scale water quality mapping (Pearce[1]) and interpretation of mixing in groundwater (Jankowski[1] and the work by Timms and Berhane[1]). Water quantity work has mainly concentrated on the development of simulation models for water management (Merrick and Williams[1] and IQQM, Beecham[1]). Mechanistic models at this scale generally lump together such complexity that the parameters have to be calibrated using observed data. For groundwater models these are generally piezometric observations (e.g. 3 monthly) and for river models these are generally flow and water quality observations.

A more conceptual approach to assessing landscape and catchment interactions has also emerged (Walker[1], Gilfedder[1], Claridge[1]). These approaches concentrate more on identifying areas of hazard and risk and broad analysis of trends, and are intended for prioritization and planning over large areas with limited data. The advantage of these models is that they are conceptually simple and can be easily parameterized. This allows the identification of different scenarios and their effects on natural resources. None of these models attempts to quantify uncertainty of the estimates.

Surprisingly few studies provided any insights into the critical question – deep drainage, where is it going? The northern MDB contrasts with southern Australia, where groundwater systems are often 'full', deep drainage is reflected in baseflow in streams (Friend[1], Walker[1]), streams have a high proportion of baseflow and catchment salt balances indicate net export of salts (c.f. rainfall inputs) (Walker[1], Jolly *et al.* 2001). In contrast, streams in the northern

MDB often have a low proportion of baseflow and catchments are storing salt (Walker[1]), and streams are losing water (to groundwater and/or evaporation) over long sections across the plains (Beecham and Johansen[1]). Groundwater systems often have falling water levels where they are pumped (Williams[1]), that is, where water is of good quality. In the Queensland MDB (QMDB), where investigations were conducted specifically for salinity purposes, many surface groundwater systems are relatively 'empty', vary widely in depth to water (e.g. 5-50m), and are moderately to highly saline (in Qld, Pearce[1]). No trends are yet available.

It is difficult to get a clear picture of water level trends that might indicate increased deep drainage due to land use changes due to: (a) the limited monitoring networks available, (b) short duration of records, (c) the possibly long response times involved, (d) the short time of land development, (e) nearby pumping in some cases, and (f) climate variability.

In one case, the Lower Namoi (Merrick[1]), there was some notion of recharge rates (or at least volumes) from groundwater monitoring and modeling. There seemed to be a disparity between observations of deep drainage at or below the rootzone (under irrigation) and the observations of recharge. During discussion it was said that the groundwater model does not indicate any effect of agricultural deep drainage, but does indicate recharge from streams. However, Merrick's paper (see Table 1) indicated that 'rivers' provide 57% of the inputs to groundwater while 'rain and floods' provide 29%. The latter is presumably diffuse recharge that would include any deep drainage from irrigation had it reached the water table(s). Also, water quality data indicates leaching of NaCl salts from the surface, but the temporal scale cannot be confirmed. Deep drainage estimates range between 20 and 150 mm/yr (Weaver[1]), but these apply only to years and fields where irrigation occurred, and only to a few sites. There are data that suggest drainage rates under irrigation are considerably lower for sodic Grey Vertosols in the Namoi than on some other clay soils (Montgomery[1], Zischke data in Silburn and Montgomery 2004). It would clarify this apparent disparity if the areas subject to various land uses (especially the area actually irrigated and non-irrigated) and their best-bet drainage rates were contrasted with the area represented in the groundwater model.

In areas where the groundwater table is shallower (such as the Macquarie valley or further south), deep drainage and recharge estimates appear to be more aligned.

Part of the difference between estimates of drainage and recharge is probably due to differences in objectives between groundwater studies and (agronomic) deep drainage studies and the complexity of the system at the broader scale. This complexity forces calibration of the broad scale simulation models and, due to the non-uniqueness of the posed problem, calibration can be achieved in different ways. While groundwater studies seem to have concentrated on water availability and thus have parameterized for that, agronomic studies have traditionally focused on runoff and are now refocusing on deep drainage.

There is still uncertainty about the interaction between rivers and groundwater. At the broad scale, the interaction appears to be:

- Gaining streams in upper catchments (though baseflow is often still small)
- Losing streams in the lower catchment

However there appear to be exceptions. The work by Buchanan[1] indicates that the Darling River around Bourke might receive groundwater flow due to irrigation, although the input of salt might be limited by a lens of fresh water around the river and the different densities of salt and fresh water. Similarly IQQM modeling suggests that the Darling is gaining at the lower end of the Macquarie River (consistent with groundwater discharge knowledge). This may have a major impact on river salt loads, since the regional shallow groundwater system in many of the alluvial valleys are slowly moving west towards the Darling River. If there is a long-term increase in salinity in the regional systems, as observed in parts of the Lower Namoi (Jankowski[1]), this would affect long-term salt delivery. Such a scenario is consistent with salt balances in the northern catchments (Walker[1]), which indicates that the regional groundwater systems are still gaining salt.

- Inclusion of groundwater-surface water interactions in the Groundwater Flow Systems Framework. **(Recommendation)**
- More research is needed focusing on groundwater–surface water interactions, a source of groundwater recharge and/or discharge. **(Recommendation)**

The IQQM model is now capable of routing salt through the river networks (Beecham[1]). However, this applies only to the current hydrologic behavior and salt-flow relationships used in its calibration. That is, it cannot predict effects of alternative scenarios, for example, land use or climate change. Further work is required to develop tools that can estimate flows and salt loads for alternative land use scenarios in sub-catchments that can be fed into the IQQM model. The CRC Catchment Hydrology project '2c' (Gilfedder[1]) will make some initial steps in this direction. (See also section 4.1)

Only a few truly integrated studies exist at the catchment (i.e. river basin) level. One of these is the natural resource mapping and interpretation work in the Lower Balonne catchment (Wilkinson[1]). An important outcome, for the purpose of this workshop, is the development of a conceptual groundwater model for the area, one of the few available for non-irrigated areas (Pearce[1]). This study shows there are major advantages in integrated studies in which access to data and information is well coordinated. However, as pointed out by the researchers involved in this work, integration of work between different organizations and researchers takes time and money, and this is often not explicitly budgeted for in funding applications. It is rare for enough funding to be available to cover all of the 'layers' of work required for a truly integrated study. Even in this case, further work is required to use the information obtained, e.g. monitoring trends over time, modeling the groundwater response.

- Incorporation and covering of costs of integration and cooperation between science groups in funding proposals is needed. **(Recommendation)**
- Funding organisations, which fund components of a larger project should look more closely at aligning priorities and outcomes to allow more integration between projects, without requiring duplication in reporting etc. **(Recommendation)**

As a result of this lack of funding for integration, much of the data from older studies are still stored on individual researchers PC's and filing cabinets. Compiling metadata and tidying up data to make them publicly useable is time-consuming and therefore expensive, but is rarely included in project budgets. State and federal organizations are starting to collate data, but much of these data are low level information or are difficult to integrate across data systems, and not useful for more detailed modeling. In addition, organizations are establishing their own databases, and cross-linkage is not always obvious.

- Funding for data integration should be a standard component of all research projects. **(Recommendation)**

- Integration or linkage of University and CRC data into existing databases is matter of priority and issues of intellectual property should be investigated, especially since the data collection was mainly funded by the taxpayer. (**Recommendation**)

The main points from the landscape integration are:

1. There is still little knowledge of the effects and trade-offs of deep drainage at the catchment scale and the resulting socio-economic impacts.
2. There are still difficulties in reconciling groundwater recharge, groundwater quality and deep drainage estimates at the catchment level.
3. Few integrated studies exist and there are difficulties in integrating past/separate studies due to differences in desired funding outcomes and the cost of integration.

3.5 *Risk and the future*

Although salinity hazard mapping is by now reasonably well developed, for example using groundwater flow systems, there is still more work required to convert this intrinsic hazard into real risk. Composite index methods (Biggs and Brough 2002, Claridge and Silburn[1]) are one approach, adapted from the hazard mapping used in Queensland (Gordon *et al.* 2002). In this approach, the climatic/rainfall excess layer is replaced with a deep drainage data layer (e.g. Silburn and Owens[1]), which includes the influence of land use. Furthermore the probability of deep drainage can be used. Inclusion of uncertainty is still lacking, even though some uncertainty analysis is intrinsic in the probability approach.

Gilfedder[1] presented a framework for simulation models at several scales. The ranking of the models was not based on the spatial scale, but based on the purpose and level of outcome. Identified were:

- First order models, which are broad scale and conceptual, and can be used, for example to assess management options for the Murray-Darling Basin.
- Second order models, which are more detailed/mechanistic and allow catchment level identification of management and more targeted options, for example catchment scale MODFLOW and IQQM simulations.
- Third order models, which are local-scale and often mechanistic that can be used to assess local management options, for example SWAP and APSIM.

Risk mapping is probably best developed at the first or second order model level, and uncertainties should again be included in the final product. Increasingly, local-scale models are used to provide spatial data and/or land-use relationships for the other types of models. Third order models are capable of comparing effects on drainage of factors such as climate, soil, crop/vegetation systems and land management practices. The issues of scale and validation/credibility aside, this is difficult to achieve with other levels of models. In general, these are required as inputs to the other orders of models.

4 What are still issues

4.1 *Deep drainage… so-what? Scenarios and trade-offs at the catchment scale*

There is still little known about the actual effect of levels of deep drainage on the total catchment water and salt balance. Broad-scale (first order) models, which attempt to capture the conceptual relationships, can be used to study possible effects. However, these have inherent limitations. For example, composite index hazard mapping (Gordon *et al.* 2002) cannot predict the temporal scale and the magnitude of the effects, while BC2C (Dowling *et al.* 2003) estimates the temporal scale but the final magnitude is more or less predetermined. However, with our current state of knowledge, these models offer an excellent opportunity to deliver trade-off scenarios for community consultation. The conceptual structure generally makes the models easy to understand and allows community groups to interact with the different scenarios.

The National Catchment Classification programs (NLWRA and MDBC) have greatly increased understanding of groundwater and salinity processes, and management options (e.g. Cresswell *et al.* 2003). These studies show that using case studies can provide great insights, so long as they can be classified into and compared with like-type systems (i.e. using the GFS system). However, these have mainly involved catchments that had already reached or were approaching groundwater equilibrium, i.e. 'full' systems. In contrast, in the northern MDB we are probably dealing with groundwater systems, and vadose zones, ranging from near empty to filling status, with some notable 'full' systems (i.e. the few current salinity expressions, Brymaroo, etc). Thus we may need to use approaches that are less dependent on groundwater data and trends than used in the Catchment Classification studies. The increased deep drainage since land development may be stored in, and slowly filling, the historic deficit in the vadose zone.

- ➢ Case studies, in the context of defined GFS classes similar to the Catchment Classification program, are required in northern MDB catchments to determine the future state of hydrology, salinity and salt exports. **(Recommendation)**
- ➢ Integrated studies, such as the Lower Balonne study, should be carried to their natural conclusion, which is to model the water and salt balance of the system (soil/ vadose zone/groundwater/streams) under various land-use scenarios. This should involve simple approaches and may involve more complex numerical models. **(Recommendation)**

4.2 *Deep drainage versus recharge & preferential versus matrix flow*

The apparent mismatch between deep drainage and recharge estimates is a matter of concern and should be further investigated. In particular, studies should be conducted on processes in the vadose zone (between the rootzone and the groundwater table), enabling linking of the two processes. This would also clarify the time lag involved in flow through the vadose zone. It is particularly important to investigate whether the mismatch is due to misrepresentation of the landscape scale processes, due to long lag-times or due to changes in the water flux in the vadose zone.

This also links to uncertainties regarding the occurrence of preferential flow versus matrix flow. It is still unclear which of the two processes is the dominant process in the vadose zone, and how this would affect our predictions of groundwater table dynamics and water quality effects. Drainage lysimeters are starting to give insights into these processes (Bell[1], Silburn[1], Young[1]). They measure the total flow (so don't miss preferential flow) and recent results indicate that preferential flow can be separated from the total. Combining this with tracer studies should give informative results. This type of work needs to be extended deeper into the vadose zone (e.g. Rick Young's lysimeter at 6 m depth).

- ➢ There is a need for a research into water and solute movement processes in the vadose zone to link surface water and groundwater processes. In particular, this should investigate the implications of these processes for landscape scale assessments. **(Recommendation)**

4.3 *Appropriate scales, extrapolation & uncertainty of models and measurements*

Uncertainty of measurements and model outputs is often not included in reports or publications. This is an important aspect that could improve the reliability of, and the confidence the community has, in the outcomes of scientific research. In addition this would limit the use of models or measurements outside the appropriate scale, since the uncertainty of the measurements or predictions would increase substantially.

4.4 *Integrated studies at the catchment level*

There are few studies and projects that incorporate all elements of the catchment. This means that important connections could be missed and the overall understanding of cause-and-effect relationships at the catchment level are not well understood.

To enable such studies there is a great need for funding agencies to align the desired funding outcomes and to allow for funding for cooperation and integration in project budgets.

4.5 *Effects of, and on, water quality*

Research on the quality of irrigation water on deep drainage and effects of deep drainage or recharge on the quality of groundwater is still relatively limited. If stream or groundwater water quality declines, there will be consequences for management of irrigation, and indeed other water users. There is a particular need to look at temporal changes in groundwater quality, rather than an overall static assessment. This would involve collating irrigator information and sampling to assess overall quality of input and short time temporal sampling of groundwater to assess seasonal changes in groundwater quality.

4.6 *Data integration and management*

More needs to be done to integrate and manage existing and new data from research projects. In this era of fast computers and simulation models there is an immense need for data and although much data exists, it is of varying quality. There is a real need capture and integrate at least key existing data from the Northern Murray-Darling with sufficient metadata to make it useable by all researchers in the area. In conjunction with this, there is the need to develop a project on the IP needs and requirements for such a database and how this can be addressed within the structure.

5 On we struggle... is there light at the end of the tunnel?

by Willem Vervoort

What are our real goals in managing water balances in the Northern Murray-Darling Basin?

We would like to develop management systems for local areas with confidence in our understanding of the overall catchment water and salt balances.

In this second workshop it is clear that we have moved from "we know nothing" to "we know something", which could be interpreted as progress. However, in order to really progress we need to manage our research and knowledge generation in such a way that the outcomes of the individual research projects all work seamlessly towards such a common goal. This overall goal can be divided into three main areas:

1. We need to make sure that our studies cover all of the biophysical space in sufficient detail. Where real data collection and sampling is not possible we need to have simulation models, which accurately represent the biophysical space. "Accurately" is meant on a pragmatic level (Beven 2002);
2. We need to ensure that we (and others) have confidence in our measurements and our simulations, which means we have to quantify the uncertainties; and
3. We need to make sure that our projects are integrated and well connected, and that the individual project outcomes are thoroughly checked and tested against other results.

These are not very earth-shattering or stringent goals for research projects, but are they always addressed, and do they keep the whole Northern Murray-Darling Basin in mind?

5.1 *Biophysical*

Firstly we need to identify where the different current studies are located within the overall catchment space. As pointed out in the beginning of this report, there is substantial research going on in the area of the water balance. Researchers are working at all different scales and at different levels of detail (Fig. 1 and 2). In the first figure we have tried to identify where research is taking place in the space and time continuum. We try to identify the scales of the work in terms of time frame covered, space covered in the landscape and depth covered in the regolith. In the companion figure (Fig. 2), which is based on the hierarchy of scales model (Hoosbeek and Bryant 1992), we have tried to indicate the trade-off between detail in the study and the time and space continuum. Clearly broad-scale trade-off studies (Gilfedder[1] and Walker[1]) cover the largest space and time and depth area, but the level of detail is consequently low. In Fig 2. such studies would be located at level i+3 (catchment) in the low detail, long time span quadrant. On the other hand, lysimeter studies and deep drainage studies in irrigated agriculture tend to concentrate on the plot scale (i–1) and are short in time, high in detail, but as can be seen in Fig. 1, cover only the rootzone. Such "mapping" exercises as Fig. 1 and 2 are useful, because they can identify in which areas research gaps exist. For example, it is clear that work in the vadose zone in general, and long-term work on deep drainage is still needed.

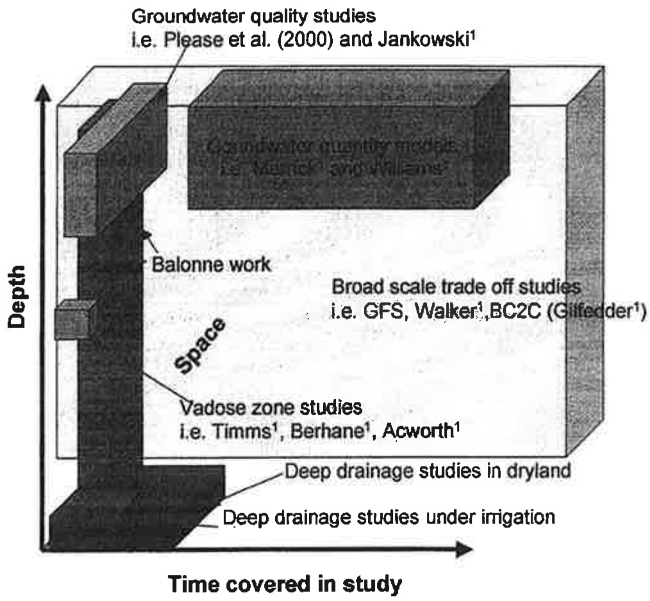

Figure 1. Overview of some projects in the space, time and depth continuum

From such an analysis we have identified at least four different dimensions (time, space, detail and depth). A fifth dimension, which is not depicted in the figures but which featured in some of the presentations (Ringrose-Voase[1], Silburn[1]), is the dimension that runs from data collection to simulation modelling. This is again related to the space and time scales, with most data collection concentrating on the short time and small space scale, while simulation studies can cover much larger dimensions.

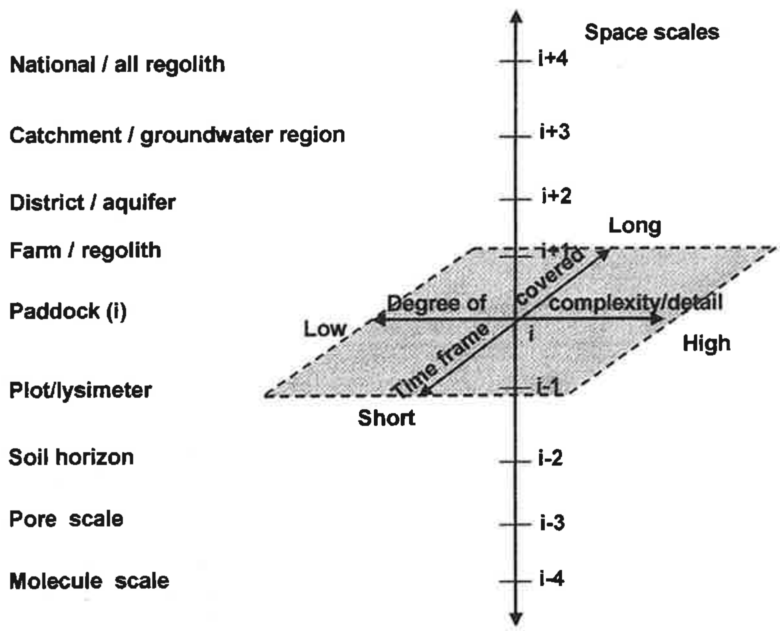

Figure 2. Hierarchy of space, time and complexity for the Northern Murray-Darling Basin studies. After Hoosbeek and Bryant (1992)

Another issue is the connection between the different scales, which appears to be lacking in the diagrams. This is true not only for the time, space and depth scales but also for the collection to simulation scale. For example, the Lower Balonne study (Wilkinson[1], Claridge[1], Pearce[1]) attempts to connect the depth scales within a larger spatial scale. This is why, in Fig. 1, it sits across a large depth and space scale, but is (currently) only short in time. In Fig. 2, it would cut across scales i-1 through to i+3, covering a low to medium complexity. It would be too much to ask the individual projects to address such a wide range of scales, but it is an important component in terms of our overall understanding of the water balance in the Northern Murray-Darling Basin.

Throughout the report we have identified several individual recommendations (see chapter 6), but these could easily be seen as projects with little linkage. Considering the current national focus on catchment management issues and the emphasis on water sharing, we believe that there are great opportunities to establish a strong research program, which actually brings together these areas of weakness. Such a research program would start off with developing a water balance spatial simulation model at sufficient level of detail that it covers the whole of the Northern Murray-Darling Basin (Darling catchment). This means that inevitably its level of detail would be rather coarse. It could, for example, be initially based on groundwater flow systems and related coarse-scale biophysical models developed by CSIRO (Gilfedder[1], Raupach *et al.* 2001). This model would function as an overall framework allowing the identification of knowledge gaps and areas of high uncertainty such as identified during this workshop. From this framework other projects could be linked into the overall model (such as IQQM results, Beecham[1], deep drainage 'mapping', Claridge[1]), meaning that the outcomes of the individual models need to be compatible and useful as inputs into the NMDB model. Clearly such a framework would allow "zooming" to different scales and detail depending on the availability of research in that area. Note that in this case we are talking about a dynamic model, not a collection of static maps. The outcomes of such a dynamic model could be integrated as static maps into existing GIS databases such as the National Land and Water Resources Audit.

Such a research program would cut across agencies and organisations and as such could best be driven by a confederation of organisations all gaining and participating at different levels. An example of such a confederation could be a CRC or the MDBC, but could also be a more loosely defined coordination framework.

The NMDB model, by being an overarching framework over all the projects in the area would also improve the collation of data and inclusion of data into simulation models. The coherence and interaction between the different components would be more visible, making relevance of the individual research projects clear.

The research program suggested here sounds like another "mega-project" designed to attract funding money. We would like to point out strongly that this is not the case. The program suggested here would almost grow by itself, by identifying links between existing projects and enhancing the exchange and use of data. The overall model would have to be developed, but there is already work in that direction. The current data collecting exercise undertaken by MDBC (Akeroyd[1]) could also serve as a base for this program. The program need not be "owned" by any one organisation, but should be a voluntary cooperative interaction to each organisation's mutual benefit. This might sound utopian, but we believe that all of us are utopian at some level to be involved in natural resource management.

5.2 *Methodological*

The second overall aim is to ensure confidence in our predictions and measurements. As well as ensuring we have sampled the environmental space sufficiently, this means we have to quantify the absolute or relative uncertainty in our measurements and predictions to be able to better compare studies and improve integration. As has been pointed out, we now have a much better understanding of the different methods for estimating water balance components. However, we also identified that there was a lack of quantification of the shortcomings and uncertainties. Uncertainty can be defined on two levels. The first level is the uncertainty in the actual measurement (or the lack of accuracy of the measurement). This is often one of the real problems in water balance research, as identified in the first water balance workshop. The second level is the uncertainty in predictions from simulations (and this second level in fact also contains two types of uncertainty, i.e. Krzysztofowicz (2001)). In our case, the two broader types of uncertainties need to be tackled at those two different levels. The first uncertainty is well recognised and its quantification should be included in all reports on measurements. An example of such definition of uncertainty can be found in Minasny and McBratney (2002). Its inclusion in results is extremely important to be able to quantify the second type of uncertainty using stochastic modelling.

Stochastic modelling is used increasingly to assess the uncertainty due to variability in simulation model input parameters (or uncertainty in input parameters) (Krzysztofowicz 2001). Limitations to this technique are mainly due to the lack of computer power (which is increasing rapidly) to repeatedly run simulations and summarise the results, and the difficulty in generating the necessary statistically correct distributions of inputs. Many soil water and catchment models lack an easy-to-use module with which to generate distributions of input parameters and readily interpret the outputs. An example of a model that generates input distributions is the Excel module @RISK (Palisade www.palisade.com), while BROWSER (McClymont *et al.* 2003) developed by QNR&M is an example of a tool that can quickly summarise output. Another example is the parameter estimation tool PEST (Doherty 2002), which can 'wrap-around' most models and perform this task if the model is calibrated.

The groundwater flow systems framework (Coram *et al.* 2000) has been very useful to identify, on a broad scale, groundwater systems which are more responsive to management (local) than larger less responsive systems. Clearly from this workshop, it is noted that this framework needs to be expanded to extra levels of detail. An example of such detail is the development of the G-parameter (Gilfedder *et al.* 2003), to quantify the hydrological behaviour. Incorporation of surface water groundwater interactions, such as suggested in this workshop, would further enhance the framework. This would then allow making the connection between the "qualitative" mapping and hazard analysis, and the "quantitative" dynamic modelling and risk analysis.

These methodological points would greatly enhance and fit well with the research program suggested earlier. By identifying and quantifying the uncertainty in the overall NMDB model it will be easier to identify gaps in knowledge, while the expansion of the GFS classification could form the basis of the framework.

5.3 *Institutional*

The third goal relates to the seamless integration of projects and the free flow of information between projects. Funding and research organisations are more critical about overlap and consistency with existing research in proposals. But, despite these efforts, integration and communication of projects, knowledge and information is still one of the greatest shortcomings of the scientific community. This is not to say that papers and reports are not being published and read, or that proposals are not scrutinised carefully enough. Apart from the Murray-Darling Basin Commission, there is no integrating force for research in the Northern part of the Basin. The MDBC itself tends to concentrate more on the southern part of the basin, which is understandable considering the more pressing needs.

For individual researchers, several major forces are working against integration, and in this workshop several of these points were raised: the competitive nature and limited time frame of funding and the specific demands in desired outcomes; the lack of recognition and funding of the costs of integration and data collation; limited "technical" research databases (including methodologies and outcomes of projects) leaving only the library as a major resource; the lack of clear IP protocols for data sharing and use.

- There is a need for national protocols for sharing and use of data from research, which recognises the first rights of publication and ownership. (**Recommendation**)

As a result, research is still duplicated and data and information are lost. The suggested research program could act as a focus to collate technical data and facilitate use of data in simulation models, which in turn are the most powerful tool available to assess catchment behaviour and compare management scenarios. We will need to admit that, given the Australian biophysical space, it is impossible to develop sufficient policies or management options based on measured data. This means we will have to maximise the use of the existing data by employing simulation models. Improving the free flow of information and encouraging the use of data in models is therefore extremely important.

5.4 *The Northern Murray-Darling – Water Balance Group (NMD – WBG)*

All these goals seem extremely utopian, after a more detailed inspection. In particular, if all these good intentions have to be integrated across the whole of the Northern Murray-Darling basin (Darling catchment for purists). And maybe it is. But whether we will ever achieve our goals is another matter, but we can at least strive in such a direction.

To establish the suggested research program on a voluntary basis, there is a need for a specific technical forum to communicate ideas and knowledge on different topics. This is particularly true for water balance issues in the Darling catchment of the Murray-Darling Basin, where there are few other such forums.

The NMD–WBG was established to provide a technical forum specifically for researchers and, at the same time, create a vehicle for coordinating and communicating research in the water balance area in the Northern part of the Murray-Darling Basin (the Darling catchment). This includes both surface water and groundwater processes, because we believe that all these processes are connected within the landscape. It specifically wanted to address the need for technical communication about issues surrounding water balance research. The NMD–WBG is supported by the organisational structure of the Australian Cotton CRC, but encompasses both dryland and irrigated research in the fluvial clay plains and upland areas. Although the group is currently only a core, it can grow into a strong and useful communication avenue for researchers. It links into the existing database and information network through its mother, the Australian Cotton CRC, and through the representative organisations, but remains concentrated on technical issues. The group currently consists of a core of researchers, all of whom represent their different organisations, but work together in a voluntary and truly cooperative manner. In future, this core will build into a wider network of research and extension personnel through regular workshops and communication avenues.

Some of the major tasks that are planned for the NMD–WBG are:

1. Building of a database of research and research issues in the area. This should list technical details of the research, such as scope and limitations of the work, technical methods employed, envisioned publications and some discussion of difficulties encountered. Such a database would be a resource for identifying gaps in the existing research and identification of new methods and allow the capture research knowledge across all areas of water balance research. This could eventually grow into the suggested modelling framework.
2. Coordinating and advising on existing research through a body of research knowledge. This could be in the form of workshops, mailing lists, discussion forums and newsletters. The emphasis should again be on technical issues, availability of data and information and not on highlighting research outcomes and achievements.
3. Coordinating the capture of existing research data in databases and wider validation of models using such data (by **any** interested modeller). This would also involve transformation of data into common formats. This can be started even before IP issues are sorted out, on a voluntary basis, and based on existing reports and publications. Too few models are cross-validated on different data or against other model outcomes. We all prefer to work with our favourite model and don't look across the fence often enough. This comes back to the costs of cooperation and IP issues.
4. Facilitating integration of research between different organisations and for example Cooperative Research Centres.
5. Highlighting research outcomes and further needs to the wider community.

6 Summary of recommendations from the workshop

6.1 *Biophysical*

- Case studies, in the context of defined GFS classes, similar to the Catchment Classification program, are required in northern MDB catchments to determine the future state of hydrology, salinity and salt exports.
- Integrated studies, such as the Lower Balonne study, should be carried to their natural conclusion, which is to model the water and salt balance of the system (soil/ vadose zone/groundwater/streams) under various land-use scenarios. This should involve simple approaches and may involve more complex numerical models.
- More research is needed focusing on groundwater–surface water interactions, a source of groundwater recharge and/or discharge.
- There is a need for research on water and solute movement processes in the vadose zone to link soil water and groundwater processes. In particular, this should investigate the implications of these processes for landscape scale assessments.
- Data from previous and current deep drainage/soil water balance studies needs to be captured and used to validate and parametise the models that will ultimately be used to extrapolate results. (urgently, its drainage away!).

6.2 *Methodological*

- Inclusion of uncertainties of measurements with all studies to improve cross comparison of research
- Development of modules in models, which allow stochastic simulations and statistical summaries of outputs. This would improve the estimation of uncertainties.
- Inclusion of groundwater–surface water interactions in the Groundwater Flow Systems Framework.

6.3 *Institutional*

- Recognition and incorporation in funding arrangements of the costs of integration and cooperation between different research groups.
- Alignment of priorities and outcomes by funding organisations that fund components of larger projects. This will improve integration.
- Incorporating funding for data integration in all research projects.
- Integration and linkage of University and CRC data into existing databases should be a matter of priority, and IP issues should be investigated.
- There is a need for a national protocol for sharing and use of data from research including recognition of first right to publication and ownership.

6.4 *Communications and delivery*

- Results from on-going water balance studies should be included in CRDC's WATERpak[4] updates. This is important since new information is available every year.

[4] WATERpak, version 1, is to be released in June 2004 by CRDC.

The proposed "CRC for Cotton Catchment Communities" and other related CRC's could be an important avenue for achieving some of these recommendations, and should include some of the suggested activities.

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8 Workshop agenda, speakers and topics

Wednesday 19th November 2003.		
Opening	Guy Roth, CEO Cotton CRC – why are we here? What do we need to do?	
1. Deep drainage and soil water balance		
a) Session 1 - Dryland		
	Presenter	**Presentation title**
	Chair: Anthony Ringrose-Voase	Co-chair: Willem Vervoort
01	Anthony Ringrose-Voase & Mac Kirby & (CSIRO L&W)	Setting the scene. What is deep drainage & recharge, how to measure/estimate it?
02	Rick Young & John Friend (NSW Ag)	Review: Drainage under dryland farming systems in NSW
03	Mike Bell (QDPI)	Deep drainage on permeable soils that aren't at depth!
04	Mark Silburn (QNRM)	Deep drainage under dryland ag in QMDB – the trilogy
05	**Discussion:** technical difficulties, uncertainty, how do we capture this data in a useable form? Scale and extrapolation in space & time. What does this mean for salinity?	
10.35	Morning break	
b) Session 2 - Irrigation		
	Chair: Ted Gardner	Co-chair: Mark Silburn
06	Ted Gardner (QNRM, NIPSI)	Setting the scene: history of irrigation & of drainage research 101.
07	Tim Weaver (NSW Ag, Cot CRC) Janelle Montgomery (UNE, Cot CRC)	**NSW Stories:** Review of DD under irrigation in N-NSW
08	Mathew Bethume (Victoria)	Review: southern irrigation drainage work
 09 10a	 Des McGarry (QNRM, CRC-IF) Steve Raine (NCEA, CRC-IF)	**QLD - DD under irrigation:** "... in QMDB & links to CRC-IF" Review: NCEA - fields, channels & storages
10b	Steve Raine	Field-level deep drainage risk assessment, tools and irrigation management
11	Graham Harris (QDPI) Cotton CRC	Comments from 'clients' – lead to discussion
12	**Discussion:** technical difficulties, uncertainty, how to capture data in a useable form? Scale & extrapolation in space & time. What more to do? Extension opportunities? '*those who don't capture there data in models are destined to re-measure it!*'	
1 pm	Lunch	
2. Where have the water & salt gone and what is it doing?		
Session 3 - Groundwater stories from various regions		
2 pm	**Chair Glen Walker**	
	Presenter	**Presentation title**
14	Glen Walker (CSIRO, CRC-CH)	Groundwater systems (GFS) in NMDB & the salinity context of groundwater
		Northern NSW stories:
15	Mike Williams (DIPNR) (Bryce Kelly)	Groundwater systems in N NSW and what's in them.
16	Noel Merrick (UTS)	Groundwater flow model of the Lower Namoi Valley
17	Wendy Timms (UNSW), Dawit Berhane (DIPNR)	Point measurements of GW recharge – linked to deep drainage?
18	Jerzy Jankowski (UNSW)	Geochemical effects on over extraction of groundwater
3.25	Afternoon break	
19	Sam Buchanan (Sydney Uni)	GW-surface water interaction near Bourke
20	Bruce Pearce (QNRM)	Groundwater systems in QMDB and what's in them
21	**Discussion:** Is 'new' deep drainage affecting groundwater? Climate or land use? Time-lags. Interactions with streams. How does this affect salinity in N-MDB?	

Thursday 20th November 2003.		
8.30	Guy Roth - Summary of main points from yesterday	
Session 4 - Integrating the story.		
	Chair: Mac Kirby	
Integration: Lower Balonne salinity and groundwater case study		
22	Kate Wilkinson (QNRM) (M. Grundy)	Overview of a collaborative approach
23	Andrew.Fitzpatrick (CRC-LEME)	Airborne electromagnetics and application to salinity and groundwater mapping
25	Justin Claridge (QNRM)	Surface soil, landuse, water balance
25	Bruce Pearce (QNRM)	Groundwater conceptual model
	Discussion: how do we do salinity assessment? How do we do it everywhere?	
10am	Morning break	
Session 5 - Where is the water & salt coming out? Landscapes and rivers.		
	Chair Michele Akeroyd (MDBC)	Co-chair:
26	Michele Akeroyd (MDBC)	Basin salinity management strategy, atlas etc
(a) History – rivers		
27	Glen Walker (Ian Jolly) (CSIRO)	Salt balance of MDB rivers – will the north end up like the south?
28	Richard Beecham (DIPNR) & Craig Johansen (QNRM) (jointly)	N-NSW & QMDB river salinity and salt loads
(b) Future – secret salinity spatial modelling		
29	Justin Claridge, Mark Silburn (NRM)	Salinity *hazard* mapping & how to '*do risk*'
30	Willem Vervoort (Claire Glendenning) (Sydney Uni)	Deep drainage risk mapping Border Rivers
31	Matt Gilfedder (CSIRO, CRC-CH)	Broad scale priority setting for land use change to impact river salinity & Project '2c'
	Questions & discussion	Model rich and data poor? Critical data? Best method? Critical next steps?
Discussion & wrap up		**Guy Roth & WBGroupies**
	Managing the water & salt balance. Future research & extension needs. Gaps. Meta-databases, mapping, data availability. Initiatives and options for cooperation? What role could the "new" cotton CRC play? Where does the NMD – WBG go from here?	

9 Main points from workshop presentations and discussion

Compiled by Willem Vervoort

Session 1A: Deep drainage (DD[5]) under Dryland	
1. Anthony Ringrose-Voase, Mac Kirby	'Setting the scene. What is deep drainage & recharge, how to measure it? ▪ Deep drainage is episodic. There is a need for a longterm view. The 5 year mean is not equal to 40 yr mean, i.e. the distribution of DD values is skewed. ▪ The Northern Murray-Darling Basin is different, due to summer crops in summer rain dominated area. This means the risk of deep drainage is lower. (Ed. – rainfall events are also larger, so the risk is somewhat increased). ▪ From an overview of methods of measuring deep drainage it appears that there is no perfect method, but less accurate methods should be combined with more accurate methods
2. Rick Young, John Friend	Review: Drainage under dryland farming systems in NSW ▪ NMDB is different since high rainfall coincides with high temperature and Vertosols are a buffer against drainage ▪ Still a lack of data and long enough data series. Need data to validate models. ▪ Landuse can be used to control deep drainage ▪ Most deep drainage point source methods are good enough to compare methods ▪ John Friend: Better to reorganise systems in the landscape than to invent new systems. (Ed. Assume means farming systems?)
3. Mike Bell	Deep drainage on permeable soils that turn out to be impermeable at depth! ▪ Red Ferrosol work indicates balance/trade-off between infiltration and runoff. Crusting occurs. However better infiltration does not equal better yields. ▪ Two effects of DD on hydrology of landscape: good quality perched water tables and salinity expression due to rise in regional groundwater table ▪ Sensing area of instruments needs to be big enough to pick up preferential flow ▪ Modelling of preferential flow still difficult
4. Mark Silburn See written submission	Review of deep drainage under dryland ag in QMDB – the trilogy ▪ Salinity occurs where: Stores of salt are high. GW is shallow, so can interact, and hydrological change occurs with land use change. ▪ Few monitoring bores are shallow (Ed. <5-50m) ▪ Deep drainage methods have useful extras in terms of research such as water quality with lysimeters, soil salt stores from chloride sampling. ▪ There is a trend in methods. Measurements (lysimeters) are accurate, but you can only have a few. Cl mass balance methods are less accurate, but can have more. Modelling can have lots, but uncertainty about reality. Doing all three. ▪ Lysimeter installed without walls, tracks soil suction status. ▪ Scale issues: what measurement measures what at what scale? ▪ Disparity between saturated topsoil and unsaturated subsoil ▪ It seems Mark's drainage is not episodic, but peaks are hidden in cumulative graph

[5] DD = deep drainage, GW = groundwater, GFS = Groundwater Flow System after Coram *et al.* (2000)

5. Discussion	▪ Decisions on scale depends what you are looking at, might have to include looking at groundwater recharge. ▪ However groundwater is complicated due to overburden pressures and if groundwater is rising it might be too late. ▪ Mike Williams: Objective is important, process understanding is needed. No change could mean discharge and recharge are in balance. ▪ M.S.: Focus of this workshop is at catchment level, effect of management actions and integration of research.
Session 2. DD under irrigation	
6. Ted Gardner	Setting the scene: history of irrigation & of drainage research 101. ▪ Queensland: groundwater rising under certain irrigation areas, most of which has high salinity. ▪ Some places no rise due to conjunctive use (pumping) ▪ Salt balance important ▪ Irrigation very important economically for Aust. agriculture. Pumping salt to the ocean (on question from Rick Young) only feasible if salt load is similar to normal river load.
7a Tim Weaver See written submission 7b Janelle Montgomery See written submission	**NSW Stories:** Review of DD under irrigation in N-NSW ▪ Chloride mass balance combined with ceramic cup samplers and water balance modelling ▪ Data shows balance between runoff and deep drainage between cotton rotation methods ▪ Some problems into Cl mass balance due to large spatial variability, preferential flow, anion exclusion values ▪ Measured all components of the water balance ▪ Spatial variation in surface flows and between water content measurements ▪ Deep drainage using Darcy's Flux uncertain due to highly variable Ks values. ▪ Cl mass balance seems to under predict DD
Questions/ discussion with 7.	▪ Variation in Cl mass balance possibly due to spatial variability or due to error. Tissue analysis show that plant uptake is very small c.f. mass of soil Cl. ▪ Cl mass balance is long term average while WB and Darcian Flux are annual values ▪ Preferential flow is not identified by Cl mass balance; could explain lower values of Cl mass balance.
8. Matthew Bethune	Review: southern irrigation drainage work ▪ Liz Humphreys has just published a review of flood irrigation DD ▪ Used 1-D finite difference model SWAP to model DD from small lysimeters. SWAP will model cracking. ▪ Great need for good hydraulic data. ▪ Effect of soil structure, if not irrigated for 10 years much higher DD ▪ Need to determine what are the most important processes determining DD ▪ Q (D. McGarry): Water content at onset of cracking is needed in the model. A: This corresponds to value on the shrinkage curve, which could be determined with Pedotransfer functions ▪ Q (T. Gardner): size of lysimeter? A: Bigger lysimeters are better, since these are less disturbing and closer to field conditions

9. Des McGarry	QLD - DD under irrigation … in QMDB & links to CRC-IF ▪ Includes Naidu Bodapati's project ▪ Barrel lysimeters using a small suction at the bottom, combined with capacitance and weather station. Radiation intercept is modelled using crop pictures ▪ Drainage varies systematically along irrigation furrows ▪ Modelling using SIRMOD, SODICS and SaLF to cross-check methods and close salt balance ▪ Q: What are interactions with the groundwater system? and what happens below 1.8m. A: ?
10. Steven Raine See written submission	Review: NCEA – leakage from fields, channels & storages ▪ Losses from dams and channels can be high, but significance at catchment level? ▪ Can increase water use efficiency by changing inflow rate and cut-off timing to decrease DD (as per SIRMOD) Field-level deep drainage risk assessment, tools and irrigation management ▪ Field data can be integrated for catchment/industry level assessment, awareness and action ▪ Farmers will optimise requirement efficiency, but can also do well with changing cut-off rate and timing
David Mitchell See written submission	Whole farm salinity management strategies for cotton production in the Macquarie Valley.
11. Graham Harris	Comments from 'clients' – lead to discussion ▪ Farmer scepticism due to inconsistent messages, but irrigators are keen to know about DD ▪ Research is uncertain due to gathering of knowledge and shifting paradigms ▪ However, Irrigators: if we don't have a problem we don't need to do anything about it.
12. Discussion	▪ Credibility of message is an issue for stakeholders ▪ M.S.: Consensus about methods, as long as there is cross-checking. However, we don't know what goes with the water, and what is excessive drainage? We need to integrate towards the landscape ▪ Bryce Kelly: split in funding and objectives between groundwater and deep drainage has created different outcomes. ▪ M.S. But state organizations now need to address the NAP ▪ W.V. How is data storage in all these projects organised? ▪ Dawit Berhane: depends on custodian ▪ A. Ringrose-Voase: Data often cannot be made accessible in timeframe of project ▪ Bruce Pearce: Under NAP, data collection and storage is implemented as an activity ▪ Steven Raine: Should look broader for data: consultants and their clients ▪ Sheila Donaldson: Data storage is happening in Govt agencies. NDSP also: groundwater flow systems. ▪ T. Gardner: Anywhere where soil physics and GW agree on DD rates? ▪ M. Williams: Not known, due to focus of funding

Session 3: Groundwater stories from various regions	
14. Glen Walker	Groundwater systems (GFS) in NMDB & the salinity context of groundwater ▪ Groundwater flow system (GFS) framework is mainly meant to identify areas where we can achieve change through management ▪ Assumptions in GFS is that groundwater processes are mainly driven by size, geology and impediment to flow ▪ GFS are mainly a focussing tool, useful over broad areas if the only tool available ▪ Q (B. Finney): Is there flow from gw to river or vice versa and what happens more often ▪ A (M. Williams): Depends on location; further West groundwater is taking water from river ▪ M.S.: IQQM identifies locations of gaining and losing streams ▪ Willem: T. Gardner asked Glen a question about why the Mallee worked (coupling gw and deep drainage), but I still don't understand the answer
15. Mike Williams See written submission	Groundwater systems in N NSW and what's in them. ▪ GW recharge occurs mainly during floods ▪ Most GW output is fresh & diffuse; GW salt to river only occurs at local spots ▪ Definite mismatch between DD and recharge ▪ GW models exists in some areas of NSW based on historic data ▪ Water use efficiency will be superseded by water allocations and environmental requirements ▪ Dry climate impacts have not been sufficiently covered ▪ There is no management of the unsaturated zone ▪ There are still questions about subsidence and social impacts ▪ Q (B. Finney): No indication of impact of groundwater by DD? ▪ A (M.W.): there is some tracking of leakage using geophysics and capture of DD is encouraged. Also GW pumping probably prevents expression of salinity problems up the catchment. (Ed. – only where pumping is possible)
16. Noel Merrick See written submission	The regional groundwater flow model of the Lower Namoi Valley ▪ GW model for the Namoi well established in MODFLOW since 1980's. 2.5 x 2.5 km cells. Recalibrated and validated several times; focussed mainly on impact of pumping ▪ Some groundwater mounding in SE due to irrigation (??) also upward pressure from GAB ▪ Flooding is major recharge, but does not seem to go through lighter texture soils. ▪ Stream signature disappears at approximately 7 km from the river. ▪ Q (M.S.): DD invisible? ▪ A: DD does not show up in the bore hydrographs ▪ Q (M. Kirby): What rate of DD would be visible and in what timescale? ▪ A: 50 – 100 mm/year should be visible, this is similar to the flood response

17. Wendy Timms and Dawit Berhane See written submission	Point measurements of GW recharge – linked to deep drainage? ▪ Attempts to bridge GW recharge and deep drainage (vadose zone processes) ▪ Basically leakage processes in aquitards, since clays act as aquitards ▪ Interpretation of piezometric levels is complex due to fracture flow (episodic and short term, preferential) and matrix flow (much slower and long term). Also storage, loading and barometric effects on groundwater levels. ▪ Under irrigation salt store is much lower and 30% of shallow groundwater appears to be recharged by DD. ▪ Suggests using a dual porosity model to capture processes, but hinges on a good description of hydraulic properties of the vadose zone
18. Jerzy Jankowski See written submission	Geochemical effects on over extraction of groundwater (Lower Namoi) ▪ Hydrogeochemical characterisation of Lower Namoi aquifer. Three layers: Cubaroo (Palaeochannel), Gunnedah (middle) and Narrabri formation (top) ▪ Evidence of upward leakage from underlying GAB ($NaHCO_3$ rich waters) and downward leakage (recharge, NaCl rich water) ▪ This process is strengthened by dewatering of middle aquifers and depends on the connection between the different aquifer layers ▪ This causes a decrease in water quality in the middle aquifer ▪ Q (B.Finney): How long before aquifers are unusable ▪ A: Difficult to say. Difficult to get exact time frame of mixing ▪ Q (W. Timms): Are we talking about long term or short term mixing? ▪ A: Very rapid mixing
19. Sam Buchanan	GW-surface water interaction near Bourke ▪ Focus on interaction of groundwater and interaction with irrigation and river in a local groundwater system around Bourke. ▪ Initial investigation indicates that Darling around Bourke might be a gaining river, but how much of this is due to irrigation? Normally these rivers would be losing in an arid environment. ▪ There are high salt contents in the topsoil (3 dS/m) around reservoirs and the subsurface salinity (11m) is also very high ▪ It appears a complex system which is difficult to manage. ▪ Q (M. Kirby): Is there any exchange of solute with the river, since the gradient is towards the river? ▪ (M. Williams): A fresh water lens exists around the Darling river which prevents exchange with salt water (Ed.: due to different densities?)
20. Bruce Pearce	Overview: groundwater systems in QMDB and what's in them ▪ Development of groundwater flow systems map in Queensland (GFS). ▪ Mainly based on remote sensing (Landsat) to identify landscape units and existing older maps and data. ▪ Main limitation: groundwater data is mainly limited to irrigation areas. There appears to be a mixture of rising and falling groundwater levels depending on the landscape position and extent of extraction. ▪ From bore data it appears that rising water levels are now occurring in the St. George irrigation area, approximately 30 years after establishment ▪ There is limited evidence of connection between groundwater and streams ▪ New boreholes are being drilled to increase data coverage ▪ S. Donaldson: A similar mapping effort is being made in NSW ▪ Q (M. Silburn): What is the salinity in new boreholes ▪ A: Very high in some places but very variable
	▪

Discussion

- M. Williams: In groundwater systems where pumping occurs, vertical fluxes are the main drivers. Otherwise horizontal fluxes are the main drivers. In the Macquarie valley, DD is a significant contribution to recharge. From the data and experience it seems DD is too high an estimate for recharge in the Namoi, while it seems right for the Macquarie (Ed: could this have to do with differences in gw depth?). There is a need for projects that integrate DD and groundwater behaviour. Science is available, but mismatch needs to be resolved.
- M. Silburn: Many DD estimates from irrigation are from 1 year & 1 field. Have we sampled the whole distribution of DD? Need relative contribution of DD from each landuse and add it up. Pumping of gw also confuses the issue.
- N. Merrick: There are different units. DD is in mm and recharge is generally in GL and ML. If you scale up the DD estimates, is this a reasonable number.
- G. Roth: units are always a problem, seem to be different units for salinity as well.
- B. Bridge: The fact that DD is not detected does not surprise. Flow in the unsaturated zone is not detected in the piezometer. Has DD reached equilibrium and has it reached the aquifer. Floods give a quick response since the infiltration is through the levees and channels, but irrigation occurs on the backplains and is a slow response and it could take a long time to reach the groundwater. In addition, movement of water from the unsaturated zone to groundwater is spatially variable and might be difficult to measure. Hydrogeochemistry seems the best way to detect such movement
- N. Merrick: This is sensible, more permeable sediments would have highest intake under floods
- B. Pearce: Some of the recharge in irrigation areas can be quite quick, but it depends on the geology and the sediments, for example the response in Emerald is quite quick
- J. Jankowski: Similar in Griffith, the lag time tends to be short if the water table is shallow.
- W. Vervoort: (in ref to W. Timms work). Is it possible that there are two fluxes, preferential and matrix flow? The preferential flow would be too quick to be identified in three monthly data (bores and piezo's) and the matrix flow is very slow and might therefore not be detected.
- B. Finney: What happens with water quality, in particular pollutants. Quality of river recharge??
- J. Jankowski: There is evidence of Arsenic in western Namoi system. There is probably also Nitrate and Phosphate. During floods water quality should improve, but there is no available data.
- N. Merrick: The regional EC map from MODFLOW shows good correlation with the flood data
- W. Timms: In the upper Namoi, Atrazine was found, possibly moving by preferential flow, there was also Nitrate in many samples
- M. Silburn: Atrazine is preserved under groundwater conditions. (Ed. See Moss lysimeter report!)
- T. Gardner: This still leaves the question what is acceptable DD? Should we be using models such as FLOWTUBE to find out if equilibrium is achieved?
- G. Walker: In dryland situations this would be very useful. In irrigation areas models such as MODFLOW would be useful
- M. Williams: GFS are important. In Qld, intermediate systems are still rising, while in NSW they are falling. This means the next Salt audit will probably come out with lower numbers for NSW
- I. Ackworth: GW models still assume homogeneity at a relatively large cell size (i.e. 500 x 500 m)
- N. Merrick: Models cannot be used without proper calibration. Most of the soil physics models do not seem to be ground-truthed against recharge
- D. Berhane: Chloride and nitrate levels in the upper Namoi are increasing. There is the need for a project to link the saturated and unsaturated zone in combination with looking at chemical fluxes. We should be using several different methods
- J. Jankowski: Chemical methods give degree of mixing and end-members (source)
- W. Timms: We need all different methods. Chemistry alone is only qualitative. The combination of groundwater quantity and quality needs more work
- M. Silburn: (Re: model calibration of N. Merrick) It is not surprising that groundwater recharge and DD do not match. The genesis of these models is an issue. Agricultural models have traditionally focussed on different issues (i.e. runoff). We need more DD data to verify the models.

Day 2	
21a Guy Roth	Summary of yesterday:
21b Bruce Finney	What do the irrigators/farmers think, what is a real priority? ▪ How important is DD in the greater scheme of things? Is it really a priority? ▪ Important: a whole catchment perspective and to integrate all the complexities ▪ We need agreement on what we know, what we don't know and the priorities
Session 4: Integrating the story, The Lower Balonne case study	
22. Kate Wilkinson See written submission	Overview of the Lower Balonne study, integrating geophysics, soil science and groundwater hydrology ▪ Currently mainly the collection and integration of data. ▪ Creating products e.g. 3-D internet graphics to allow community access. ▪ Such an integrated project highlights the difficulties in logistics in managing people in different organisations and across states ▪ The focus of the project tended to be too wide, need to focus such a project. This could be due to differences in focus from funders ▪ Amount of fieldwork related to geophysical methods is easily underestimated
23. Andrew Fitzpatrick	Airborne electromagnetics & application to salinity & groundwater mapping ▪ Geophysical data collection and integration, development of GIS layers to be used in conjunction with other data ▪ In Lower Balonne surface water-groundwater interaction appears to be mainly through Aeolian sand bodies ▪ Aerial EM can be matched with radiometrics and Landsat to give better results but extensive ground truthing is still needed ▪ Some issues with general assumption in AEM that the basement is resistive. This was not valid in Lower Balonne & thus data had to be recalibrated ▪ Thus it is important to take care in the interpretation of remote sensing data ▪ Possibly wider line spacing can be used for Natural Resource Management, which would bring down the costs of AEM (Ed: could this depend on the variability of the landscape?)
24. Justin Claridge Re: DD map - see Silburn & Owens written submission	Lower Balonne: Surface soil, landuse, water balance ▪ Development of soils information and GIS layers ▪ Original data was a combination of point and polygon data, which were combined using different weightings for the reliability of the data ▪ Used 'environmental correlation' (Ed: PTF's?) with radiometrics and DEM to develop hydraulic properties (soil attributes) ▪ Environmental correlations were low; there are problems with data extrapolation ▪ A draft DD map was developed using PERFECT and GRASP modelling ▪ Key issues for salinity risk assessment are: landscape context, interaction between the surface and deeper layers and recognition that salinity is a multidimensional problem
25. Bruce Pearce	Lower Balonne: Groundwater conceptual model ▪ Development of a bore monitoring network ▪ Combination of existing data and newly installed bores ▪ Detailed hydrogeological model for cross sections has been developed based on bore data. Further work will develop a full 3-D model ▪ Reveals 2 main aquifers and a block feature in the middle of the EW direction ▪ Older St George irrigation area shows a distinct mound in the upper aquifer, while localised pumping is visible in the lower aquifer potentiometric surface

Discussion/questions

- J. M. Kirby: How is the connection between surface water and groundwater modelled in this area?
- A. Fitzpatrick: This is not included in this model, but will hopefully be included in the next version
- B. Pearce: A further NAP project will specifically look at this interaction, but groundwater levels are well below the river
- I. Ackworth: How was the correlation AEM and the boreholes achieved?
- A. Fitzpatrick: This was through correlation of EM39 in the boreholes with the AEM data
- B. Kelly: What are ramifications of your recalibration for other areas were AEM has been done?
- A. Fitzpatrick: This depends on the conductivity of the lower basement. There is some work on developing new software to perform this on older data
- D. Mitchell: The project developed a series of pretty pictures for the community. Is this useful?
- K. Wilkinson: It was more developed to allow storage and viewing of the data. Responses from the community have indicated that they like this.
- B. Kelly: Confirms value of 3-D data
- R. Young: In development of Land management units (LMU's) in the Liverpool Plains, geophysics was not deemed useful.
- K. Wilkinson: Radiometrics come free with AEM, but for salinity hazard, added value seems low
- S. Donaldson: Important to combine geophysics with hydrogeology, not good to use one method.
- A. Ringrose-Voase: In the Liverpool Plains, geophysics was used in combination with sampling. In terms of landuse mapping, the classes are very broad, there is not enough information, since rotations are not included. There is a need for better land management information.
- J. Claridge: It is difficult to capture this & therefore also difficult to make updated maps that use it
- I. Ackworth: Can the Liverpool Plains geophysics be revisited in light of these new findings?
- A. Fitzpatrick: This depends on the digital elveation data
- S. Donaldson: NSW Dept. of Mineral Resources has the radiometrics.
- A. Fitzpatrick: Another point is that the uncertainty should always be included on the maps
- D. Mitchell: What about sodic/saline soils, can they be picked up by AEM
- A. Fitzpatrick: There was some overlap, but no real correlation between the two.
- J. M. Kirby: This seems a truly multidisciplinary project. Is this a good example for other projects in the area? i.e. what have you learned. Secondly: What are you doing about data management?
- K. Wilkinson: Really important to have a conceptual model first before running a large scale project
- J. Claridge: Establishing the links in the data is still difficult
- B. Pearce: Data from the drilling is put into a state database. A new project is trying to combine all data in a database
- J.M. Kirby: Seems that this is still a build–up out of individual projects. Is this due to the lack of clear focus at the start?
- B. Pearce: Collaboration is difficult with people in different locations and different states
- A. Fitzpatrick: I believe lack of focus at the start was a problem
- G. Walker: There are also some inconsistencies due to deadlines in funding. There is now a refocussing through the conceptual model building
- J.M. Kirby: Did the SA projects achieve linkage between surface and groundwater?
- G. Walker: The linkages were there in terms of salinity management and where we wanted to do management
- G. Harris: How is the community consultation and involvement going in this project?
- K. Wilkinson: There was a gap in giving community feedback during the reprocessing phase, since we first wanted to be sure it was right. Right now community consultation is on-going, and they should have been involved from the start
- A. Ringrose-Voase: Project is actually really good and QDNRM is leading the way. This should be looked at by other agencies

Regarding soils & deep drainage maps … ▪ M. Silburn (to J. Claridge): Having the deeper soil cores drilled has been really useful in terms of soil depth determination. What other methods have you used to improve survey methods ▪ J. Claridge: Effective rooting depth is still a difficult thing to determine with limited observations. Soil surveying is using a range of new tools to create soil property maps. ▪ T. Gardner: Are the DD values on the maps going to be checked? ▪ M. Silburn: We did paired chloride sites across the QMDB and are using them and water balance studies to validate the models. The maps need validation – they are early drafts. ▪ B. Bridge: There is a word of caution, there are "lies, damn lies, statistics and….models". The Qld "Salinity Hazard Map" is not a very good example of community consultation. We have to be careful for the use of our work in regulatory control.	
Session 5: Where is the water & salt coming out? Landscapes and rivers	
26. Michele Akeroyd	Overview of MDBC salinity management strategy and the Basin Interactive Salinity Maps ▪ Within MDBC there is a shift from river management (i.e. end-of-valley targets) to land and catchment management (within-valley targets) ▪ Management includes reviews and audits ▪ MDBC is collating existing data in a GIS based on minimum standards. ▪ Data will be available on the internet as pdf files, but Arcview data will be available on request ▪ Land use will be mapped for each year so temporal changes can be assessed ▪ Q (B. Finney). Are salinity maps moving away from being a 'best guess' ▪ A: This is continuously done through reviews and audits through the community. The Atlas is really more a review of existing work
27. Glen Walker	Salt balance of MDB rivers – will the north end up like the south? ▪ Landscape salt import and export. The Darling river currently contributes around 22% of the salt load at Morgan, but 33% of the total salt load is not accounted for ▪ Salt balance work is similar to GFS: Broad investigation to identify which catchments are working towards equilibrium. This means looking at salt output/salt input. ▪ Similarly response times of catchments can be estimated from volume/recharge flux. From this it seems that local and intermediate catchments under ??? were in equilibrium pre-clearing, while the MDB probably was accumulating salts (response time 100,000$^+$ years) ▪ Relatively speaking the change in the water balance has been much greater in low rainfall areas compared to high rainfall areas ▪ Irrigation areas are net salt accumulators (low rainfall, low response time etc.) ▪ For the Darling (NMDB), it appears there is less salt out than salt in, meaning that the Northern Murray-Darling Basin is accumulating salt
28. Richard Beecham	N-NSW & QMDB river salinity & salt loads (MDBC 'Tributaries' projects) ▪ River salt modelling by DIPNR is mainly based on IQQM. This model is used as a decision support model ▪ IQQM is calibrated at the gauging stations in the rivers with the aim to have the water balance right ▪ From the modelling results of the Macquarie valley the groundwater interactions indicate that the uplands are gaining streams, the lowlands are losing streams, and the Darling at the end is gaining again ▪ Salt flows are based on time series (very few), look-up tables of flow vs. cons (few more) and flow vs salt load (most)

Questions with 27/28	▪ Are salt loads in rainfall estimated well enough ▪ A: (G. Walker): this could be looked at, but does it have a major impact? ▪ Are the results for NMDB (Gwydir was referred to) based on very little data? ▪ A (R Beecham): Early work was only based on gw data. The NMDB is all very low in data ▪ A (G. Walker): Trend analysis does not use any models, it is an analysis of the available data and some of that was not sufficient
29 Justin Claridge, Mark Silburn	Salinity *hazard* mapping & how to *'do risk'* ▪ Estimation of salinity risk depends on scale and purpose ▪ Risk maps should include a range of different components: DD, GW, soil etc. ▪ Using a similar GIS approach to hazard mapping (composite index method) risk maps can be derived ▪ Salinity risk is a 4-dimensional problem: 2 space, 1 depth and 1 time and no single tool can be used to estimate this. Each situation might require a different strategy and data requirements depend on the scale. This should be evaluated with the stakeholders
30. Willem Vervoort See written submission	Deep drainage risk mapping Border Rivers ▪ DD risk mapping using a 1-dimensional soil-water-crop model (SWAP). Hydraulic properties using pedotransfer functions (PTF's) ▪ Spatial integration of probabilities of DD using GIS and geostatistics (regression kriging) ▪ Some Monte Carlo simulation to estimate uncertainty ▪ Variability of DD is high (episodic) and even though mean value might be 100+ mm/year probability of exceeding this value is generally low (20 -55%)
31. Mat Gilfedder	Broad scale priority setting for land use change to impact river salinity & '2c' ▪ Broad scale models to look at scale of interventions which are needed in terms of salt loads: First Order models ▪ First order models are based on simple conceptual principles: Zhang curves for ET, spatial data. Groundwater response times from slope, length and transmissivity ▪ Can discover trade-offs between, for example, water yields and salt loads ▪ CRC-CH Project '2c' is developing the next generation of models for this question, focusing on within sub-catchments eg 500-1000km^2
Discussion with 29/30/31	▪ DD is presented as risk, but DD is also needed for irrigation ▪ A (W. Vervoort): can also be seen as DD potential. ▪ Comment (W. Vervoort) At the broad scale, calibration will always be needed, increases uncertainty. Validation of model outcomes are therefore also needed ▪ Q (T. Gardner): Are you getting upper boundary condition right in irrigation ▪ A: (W. Vervoort): The upper boundary condition is the big problem, whether it is right or wrong relative to other land-uses is more important than whether it is absolutely right ▪ B. Kelly: Calibration is a money business. There are no physical data (for example K at lower depth) and calibration is the only feasible solution. ▪ M. Gilfedder (commenting on a question on his first order model): Many of the estimates of transmissivity are based on expert panels ▪ A. Ringrose-Voase: Rootzone models have been developed to be mechanistic, because we have the data to populate them. Models should be developed which can be populated with soil survey data or vice versa ▪ T. Gardner: Again there is a resource limitation and the main gap is in soil hydraulic properties

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11 SUBMITTED PAPERS:

Papers submitted to the workshop are presented in Part II of this report and are published as:

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Review

Aquifer heterogeneity and response time: the challenge for groundwater management

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Abstract. Groundwater is an important contributor to irrigation water supplies. The time lag between withdrawal and the subsequent impacts on the river corridor presents a challenge for water management. We highlight aspects of this challenge by examining trends in the groundwater levels and changes in groundwater management goals for the Namoi Catchment, which is within the Murray–Darling Basin, Australia. The first high-volume irrigation bore was installed in the cotton-growing districts in the Namoi Catchment in 1966. The development of high-yielding bores made accessible a vast new water supply, enabling cotton growers to buffer the droughts. Prior to the development of a groundwater resource it is difficult to accurately predict how the water at the point of withdrawal is hydraulically connected to recharge zones and nearby surface-water features. This is due to the heterogeneity of the sediments from which the water is withdrawn. It can take years or decades for the impact of groundwater withdrawal to be transmitted kilometres through the aquifer system. We present the analysis of both historical and new groundwater level and streamflow data to quantify the impacts of extensive groundwater withdrawals on the watertable, hydraulic gradients within the semi-confined aquifers, and the movement of water between rivers and aquifers. The results highlight the need to monitor the impacts of irrigated agriculture at both the regional and local scales, and the need for additional research on how to optimise the conjunctive use of both surface-water and groundwater to sustain irrigated agriculture while minimising the impact on groundwater-dependent ecosystems.

Additional keywords: cotton, ecohydrology, irrigation, groundwater, surface-water, hydrology.

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Introduction

In the Namoi Catchment, Australia (Fig. 1), ~112 000 ha of land is irrigated to grow a variety of crops using a combination of surface-water and groundwater supplies (CSIRO 2007). Most of the irrigated land is used to grow cotton, in rotation with other crops. The area planted changes depending on water availability, due to the highly variable rainfall patterns in the region. For the lower Namoi Catchment (Fig. 2), in the 1998–99 growing season, 82 000 ha of cotton was planted, and this fell to only 20 000 ha in the 2007–08 drought-affected season (Bruce Pyke, pers. comm., Cotton Research and Development Corporation Crops Statistics Records). To monitor the groundwater extractions, an extensive spatial and temporal groundwater-monitoring network has been installed (Fig. 1). Groundwater levels have been monitored since the 1970s, and this provides an ideal opportunity to study the effect of multi-decadal groundwater withdrawals on the watertable, groundwater head in the semi-confined aquifers, and water movement between streams and the underlying aquifers. We focus on the Namoi Catchment where the modern Australian cotton industry was established, but

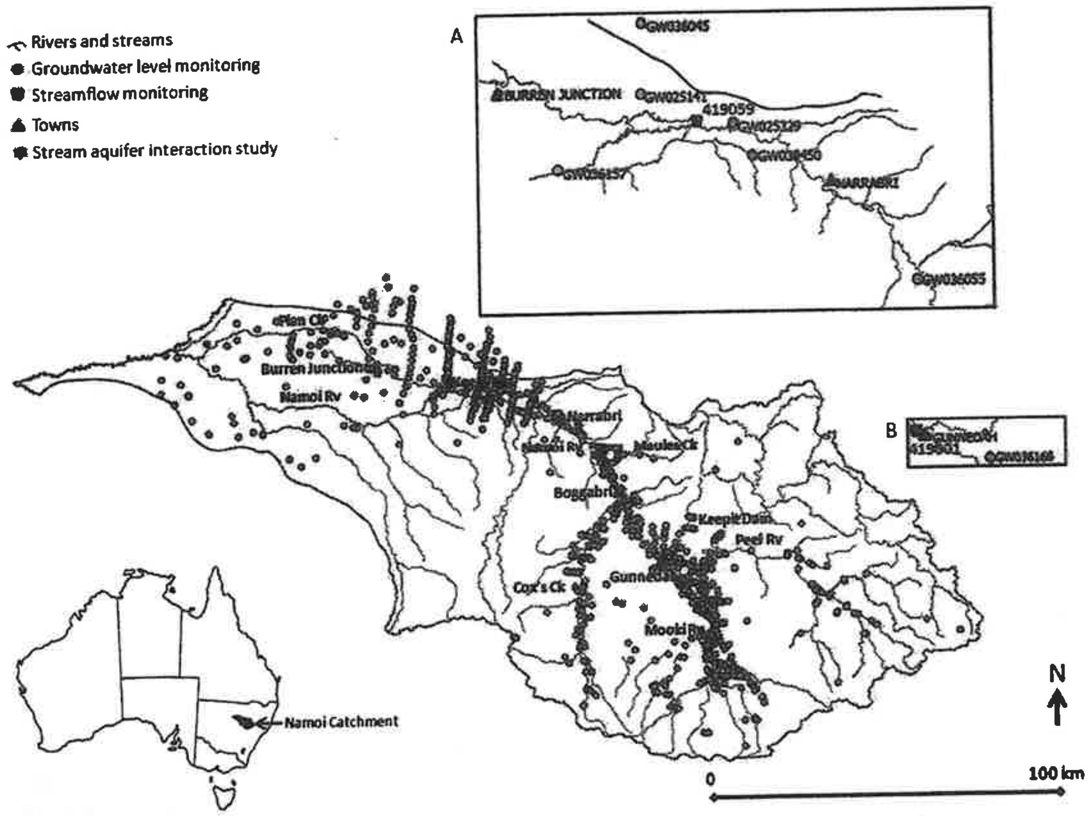


Fig. 1. Namoi Catchment location and boundary map. Note: the aquifer boundary in the lower Namoi Catchment, north-west of Narrabri, extends beyond the surface catchment boundary in the north. Locations of groundwater monitoring boreholes are shown, along with the stream and river network. Cox's Creek, Mooki River, Peel River, Maules Creek, and the Lower Namoi are all subcatchments where both surface-water and groundwater are used for irrigated agriculture. Insets A and B show the location of the boreholes used in Fig. 4.

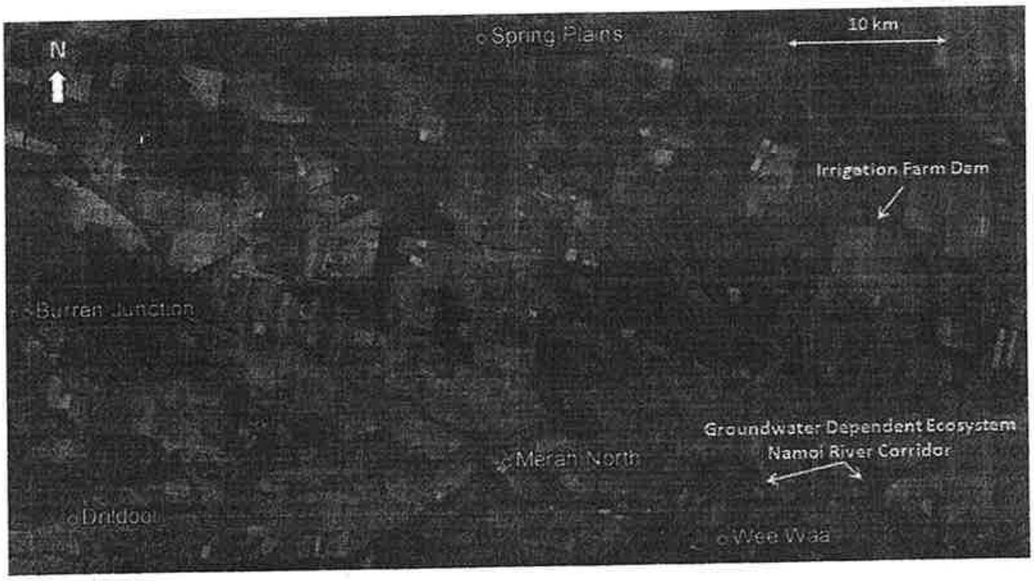


Fig. 2. Centre National d'Etudes Spatiales SPOT image (from Google Earth) of the lower Namoi Catchment. Each irrigation farm has a dam that is used for the temporary storage of water. The highlighted dam is 1.6 by 0.7 km. Some groundwater-dependent ecosystems of concern are highlighted along the river corridor.

similar impacts are observable in other catchments throughout the Murray–Darling Basin where groundwater is used to support irrigated agriculture. The observations presented have important implications for groundwater development around the world. Wada *et al.* (2012) recently highlighted that, on a global scale, groundwater use for irrigating crops is not sustainable. We highlight the need to change the way groundwater and surface-water are managed to supply water for irrigating crops.

In this paper we evaluate the impact of 45 years of groundwater withdrawals by examining trends in 458 groundwater-level monitoring records using 3D plots, correlating streamflow and groundwater hydrographs, and measuring pumping impacts on stream-and-aquifer interactions using a purpose-built monitoring network (Fig. 3). We also discuss the environmental impacts of groundwater extractions, and the goals of protecting groundwater-dependent ecosystems.

Historical background

Prior to the development of agriculture in the catchment, over the period of natural climatic cycles the groundwater discharge to streams would have been in a dynamic balance with recharge, with only minor fluctuations in the watertable occurring after floods and extended drought periods. The clearing of trees in the late 1800s and early 1900s was the first major alteration to the water balance (Reid *et al.* 2007). The large eucalypts, as well as other tree species, can be considered pumps distributed across the landscape, and removal of these trees may have reduced this natural withdrawal of water in the upper 10 m of the subsurface. There are no records of this impact, because the groundwater-monitoring network had not been installed before land clearing.

When the modern Australian cotton industry was established near Wee Waa in New South Wales in the early 1960s, it was reliant on rainfall and surface-water releases from Keepit Dam (Fig. 1). During average and above-average rainfall years, the surface-water supply was adequate to meet the demands of the irrigation sector. However, during drought years, the crops were either low-yielding or failed due to insufficient surface-water resources. In the first 4 years (1961–64) of growing cotton, rainfall was 713, 899, 911, and 966 mm, respectively. These years were wetter than average, as the mean annual rainfall recorded from 1891 through 2012 is 661 mm (Australian Government Bureau of Meteorology, www.bom.gov.au). In 1965, just 438 mm of rainfall was recorded at the Narrabri West Post Office. The relatively poor growing conditions experienced in 1965 encouraged the development of the groundwater resource. In 1966, the first high-volume, gravel-packed and screened bore for the purpose of irrigating cotton was installed on a property near Wee Waa (Courier 1967). Once proven to be economical, the use of groundwater expanded rapidly. In the lower Namoi Catchment (Namoi River reach downstream of Narrabri), where the majority of the cotton is grown, metered groundwater use peaked at ~175 000 ML $year^{-1}$ in the 1994–95 growing season (DWE 2009). The sustainable yield (locally called the sustainable

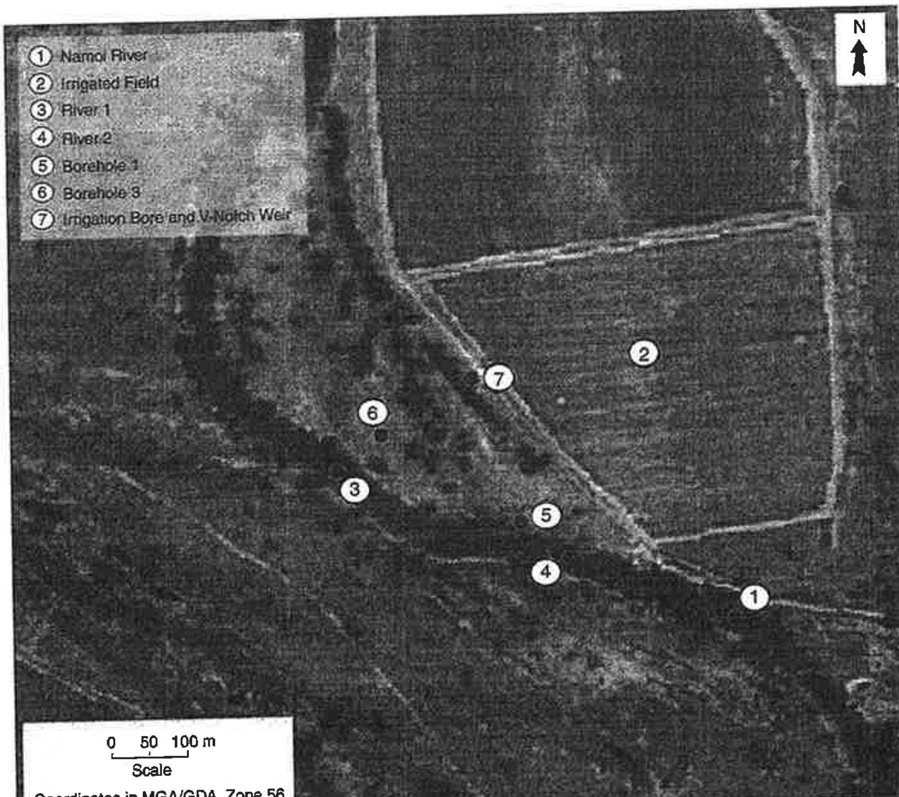


Fig. 3. Location of installations at the stream-and-aquifer interaction monitoring site, which is on the bank of the Namoi River (Site 1), in the Maules Creek subcatchment. Location 7 is the irrigation bore used to supply water for irrigating in the field denoted 2.

diversion limit) is estimated to be 86 000 ML $year^{-1}$ (NSWG 2008; DWE 2009). Staged allocation reductions aim to reach this extraction limit by the 2015–16 growing season.

The fundamentals of the impact of groundwater withdrawals via an irrigation bore (called a well in the quote below) have been comprehensively established since Theis' ground-breaking analyses in the early 1900s. Theis (1938) wrote:

> '*Discharge by wells is a new discharge superimposed on the previous system. Before a new equilibrium can be established water levels must fall throughout the aquifer to an extent sufficient to reduce the natural discharge or increase the recharge by an amount equal to the amount discharged by the well. Until this new equilibrium is established water must be withdrawn from storage in the aquifer and conversely the new equilibrium cannot be established until an amount of water is withdrawn from storage by the well sufficient to depress the piezometric surface enough to change the recharge or natural discharge the proper amount.*' (p. 889)

The above quote applies to an idealised aquifer that is well connected throughout. This idealised conceptualisation of pumping-induced groundwater level decline sets the stage for how people perceive the response of aquifer systems to groundwater withdrawals. When irrigation bores were first installed both farmers and government authorities were aware of the general hydraulic ramifications, but they could not predict with confidence exactly where there would be issues or the timing of impacts on adjacent irrigation bores, rivers, or the end of system discharge.

The fluvial systems that deposited the sediments within the palaeovalley left behind highly heterogeneous lithological sequences, and this complicates the way the aquifer system responds to pumping. Untangling the response of this aquifer system is further complicated by irregular pumping activities, major floods, and changes in groundwater management. The extensive records now enable investigation of the cumulative impacts.

There has been a substantial shift in social attitudes about how groundwater should be allocated and what impacts need to be considered. In the early documents on the development of the water resources of the Namoi Catchment, there is no reference to the impacts of groundwater withdrawals or any discussions about the ecology (Stannard and Kelly 1977).

By the 1980s, it was apparent that if groundwater were to be a long-term viable contributor to water supplies and the environmental impact controlled, then groundwater allocations would have to be altered and enforced. In the 1960s and 1970s, groundwater was allocated according to the area of designated irrigation farmland, and poor records of usage were kept. By the 1980s, this was deemed inadequate for managing the groundwater resource, and in July 1983 a comprehensive volumetric groundwater allocations policy was introduced in the Namoi (WRC 1986).

Despite acknowledgement of the impact of the overdraft on the lower Namoi Catchment alluvial system and embargoes on further development throughout the 1980s, there was still debate about how groundwater should be used. In a document discussing the reassessment of the level of groundwater entitlements and the possibility of releasing additional allocations Ross (1989) wrote:

> '*The Department's allocation philosophy for large alluvial systems such as the Namoi Valley has always been to allocate recharge* plus *a component of natural storage so that controlled depletion takes place. This means that the resource is seen as a finite resource with a limited life.*' (p. 3)

The complete transition to the goal of using both surface-water and groundwater sustainably, considering both the intergenerational use of groundwater and environmental impacts, was not consolidated until the mid-1990s with the announcement of the COAG water reforms (COAG 1994) and the policy position advice on improved groundwater management (ARMCANZ 1996). It then took another decade for the implementation of the Water Sharing Plan (NSWG 2008), which states:

> '*The vision for this Plan is ecologically sustainable groundwater sources that provide an assured supply of quality groundwater for the social and economic benefit of the people in the Namoi Valley.*'

One of the significant drivers for change in how groundwater is managed is the increased societal desire to consider the impacts of groundwater use on groundwater-dependent ecosystems (COAG 1994; NSWG 2008). The health of floodplain and riparian eucalypts has been in serious decline in the Namoi Catchment since the droughts of the early 1990s (Kalaitzis *et al.* 2000). Causes of tree dieback in the region are likely to be complex and attributable to a variety of interacting factors (Reid *et al.* 2007). Falling watertables resulting from groundwater extraction in the area has been suggested as a potential contributor to the decline in health of trees, in particular, river red gum (*Eucalyptus camaldulensis*) (Kalaitzis *et al.* 2000; Banks 2006; Reid *et al.* 2007; Reardon-Smith 2011). This concern is reflected in the Namoi Catchment Action Plan 2010–2020 (NCAP 2010), which states as a threshold target:

> '*By 2020 there is an improvement in the ability of groundwater systems to support groundwater dependent ecosystems and designated beneficial uses.*' (p. 6)

and

> '*A particularly important threshold that applies to alluvial aquifers is that the aquifer is never drawn down below historical maximum drawdown.*' (p. 54)

In this paper, we examine the effects of groundwater withdrawals at different locations throughout the Namoi Catchment, both within a kilometre and tens of kilometres away from the river, on the yearly, recovered groundwater level, and on the stream-and-aquifer interaction. We then examine some issues with the use of groundwater-level threshold targets without considering aquifer response time.

Hydrogeology of the Namoi Catchment

Groundwater that supplies the irrigation sector is withdrawn from the alluvial sediments that fill a palaeovalley formed between the late Cretaceous and the mid Miocene (Martin 1980). The palaeovalley was carved through the Cretaceous, Jurassic, Triassic, and Permian sedimentary rocks of the region (Williams *et al.* 1989). Pollen studies (Martin 1980) indicate that the climate was wetter during the mid to late Miocene when the lower sediments were being deposited. During the Miocene, the region was likely to have received ≥1500 mm of rainfall. This is reflected by the thick sand and gravel beds located at depth, which were deposited in the higher energy, wetter climate. Most of the irrigation groundwater is withdrawn from the sand and gravel units located 50–120 m below the ground surface. During the Pliocene and Pleistocene when the upper 30 m of sediments were deposited, the climate of eastern Australia was becoming drier, and this is reflected by the increase of clay- and silt-rich sediments in the upper 30 m of the unconsolidated sedimentary sequence (Kelly *et al.* 2012). The unconsolidated sediments are mostly fluvial in origin, although at the margins of the upper Namoi Catchment, there are colluvial deposits, whereas the Vertosol soils common throughout the catchment have an aeolian component (Ward 1999). The unconsolidated sediments are often divided into the Cubberoo (base semi-confined aquifer), Gunnedah (intermediate semi-confined aquifer), and Narrabri (overlying unconfined or phreatic aquifer) Formations (Williams *et al.* 1989). However, the meandering rivers that deposited the sediments have left a complex heterogeneous architecture, which in places is vertically hydraulically connected at all levels, and in other places is far more complex with many semi-confining layers throughout the vertical sequence. Furthermore, the installation of both irrigation bores and monitoring boreholes with substandard methods may in places have caused artificial vertical hydraulic connectivity through the aquifer systems (NWC 2012; Timms and Acworth 2009). This can locally alter the hydraulic gradients, and the interpretation of aquifer connectivity.

Data, materials, and methods

State government stream and groundwater hydrograph data

The primary historical datasets are the NSW Office of Water Pinneena CM and GW CDs (http://waterinfo.nsw.gov.au/pinneena). These CDs hold the complete public streamflow and groundwater monitoring records for New South Wales. The Pinneena GW CD has details on the coordinates, elevation, construction methods, casing types, slotted intervals, driller lithological logs, and groundwater levels, allowing data to be analysed in 3D. Custom Mathematica scripts (www.wolfram.com) were written to extract and analyse these data. Various state government departments with the responsibility to allocate and monitor groundwater have installed an extensive groundwater monitoring network (presently the NSW Office of Water). Within each groundwater-monitoring borehole, there can be one piezometer or more (locally called pipes). Each pipe is slotted to record the fluctuations in groundwater level for a limited aquifer interval, typically the unconfined aquifer, an intermediate aquifer interval, and near the base of the unconsolidated sediments.

Groundwater is commonly extracted from August to February. When a pump is turned on, groundwater is initially mined from storage and a cone of depression is created around the irrigation bore (Fitts 2013). This is detected as a rapid decline in the groundwater level in neighbouring monitoring boreholes. When the pump is turned off, the groundwater level in the monitoring boreholes recovers. This causes a yearly drawdown and recovery oscillation observable in some groundwater hydrographs. The groundwater-level reading in the non-pumping season, taken in June, July, or August, is called the recovered groundwater level. If the recharge contribution is in balance with the withdrawal impact at the monitoring location, there will be no difference between groundwater levels at the start and end of the pumping year. If there is a fall in the groundwater level, then withdrawals are greater than recharge for the year. This is commonly referred to as the overdraft (Harou and Lund 2008) or depletion (Aeschbach-Hertig and Gleeson 2012).

Trends in the data for groundwater level were analysed using groundwater hydrograph plots, mapping in 3D the multi-decadal change in the recovered groundwater level, plotting a histogram of the change in the groundwater level between 1988 and 2008 for all monitoring locations in the Namoi Catchment, and plotting the median annual change in the winter recovered groundwater level *v.* groundwater usage in the lower Namoi Catchment.

To identify aquifer regions that are likely to be receiving recharge from the stream, the correlation between the groundwater level recorded in each monitoring borehole and nearby streamflow records was examined. Due to the different response times of the two systems, groundwater levels tend to yield a poor correlation with streamflow. However, the relationship can be improved using the cumulative streamflow departure (CSD) (Blakers *et al.* 2011), which mimics the gradual response of the groundwater system to changes in flow. This approach is similar to the concept of using the cumulative rainfall departure curve to analyse climatic trends in rainfall (Weber and Stewart 2004). Many groundwater hydrographs throughout the Namoi Catchment display a downward trend due to the long-term effects of groundwater withdrawals. To isolate the recharge response, the hydrographs were linearly rescaled so that yearly maximum groundwater levels at the start and end of the period were equal. Finally, Pearson's correlation coefficient (r) was calculated for each pair of CSDs and de-trended groundwater time-series, using only those time intervals with complete pairs of observations.

High-frequency stream and groundwater monitoring

In addition to the long-term regional groundwater and streamflow monitoring described above, a need for high-frequency monitoring of groundwater near streams and rivers was identified. To satisfy this need, several sites were instrumented along the banks of the Namoi River. At one of these sites, observation boreholes were drilled between the Namoi River and the nearby irrigation bore (Fig. 3). Borehole 1 is relatively close to the river (~20 m) and is shallow (12.5 m below ground level; mbgl), and measures the upper phreatic aquifer. Borehole 3, which is further from the river (~70 m), has two deeper piezometers (16.5 and 32.5 mbgl). These boreholes are in a lower, semi-confined aquifer unit. They were drilled with a cable-tool rig and 50-mm piezometers were installed. Aquitard layers were sealed with bentonite and a concrete seal was installed at the surface.

At the same site, the surface-water levels were monitored in the river. Both surface-water and groundwater levels at all sites were monitored by non-vented pressure transducers at 15-min intervals. For correction of barometric variations of the non-vented pressure transducer data, a baro-logger was installed above the watertable in one of the groundwater bores at the site. This high-frequency sampling allowed accurate observations of the groundwater response to pumping and changes in surface-water flow. The pre-existing irrigation bore is further inland, ~200 m from the river (Fig. 3). Records of the screened intervals for this irrigation bore are no longer available, but it is known that withdrawal is from several intervals covering both the upper and lower aquifers (D. Eather, pers. comm.). Pumping periods and rates of withdrawal from this bore were monitored by running the irrigation discharge through a V-notch weir equipped with a pressure transducer.

Results

State government stream and groundwater hydrograph data

The water levels in the groundwater-level monitoring pipes have been manually recorded ≥4 times per year. Figure 4 shows representative groundwater hydrograph sets recorded at six groundwater-monitoring locations throughout the Namoi Catchment. A consistent scale has been used to give a sense of the change in the groundwater level from site to site. Streamflow records near the boreholes are also presented in Fig. 4.

Figure 5 displays the change in the recovered groundwater levels recorded between 1988 and 2008. These years were selected to yield the most complete spatial dataset. The change in the groundwater level was plotted at the midpoint of the slotted interval for each pipe. Figure 6 summarises the results displayed in Fig. 5 as a histogram, and shows that the modal long-term drawdown over the 20-year period from 1988 to 2008 is 4 m. The largest decline was 14.5 m, and the largest rise was 5.5 m.

Figure 7 is a cross-plot of the median yearly change in the groundwater level recorded throughout the lower Namoi Catchment *v.* groundwater usage. Figure 7 shows that for the majority of the years, the groundwater level has fallen. For the lower Namoi Catchment, groundwater-level rise within a year has been as high as 1.2 m due to recharge from floods.

Groundwater withdrawals and floods propagate characteristic water-level signals throughout the groundwater and streamflow hydrographs (von Asmuth *et al.* 2008; Beven 2012). This is clearly observable in Fig. 4*e* and *g*. There should also be responses in the groundwater hydrographs due to continuous river leakage, areal (diffuse) rainfall recharge, irrigation return (deep drainage), valley edge (mountain front) recharge, and, in a small portion of the lower Namoi, artesian recharge from the Great Artesian Basin (McLean 2003). On the alluvial plain, areal recharge estimates range from 32 mm year^{-1} in the Upper Namoi (SWS 2012) to 0 mm year^{-1} in the western portion of the lower Namoi (Timms *et al.* 2012). Areal rainfall, irrigation deep drainage (Silburn and Montgomery 2004; Hulugalle *et al.* 2010, 2012), and valley edge recharge do not cause visually discernible signals in the groundwater hydrographs.

The results of the correlation analysis between the streamflow records and the groundwater level data are displayed in Fig. 8. Positive correlations highlight which reaches of the stream/river network are likely to be hydraulically connected to the underlying aquifers that have a short lag response to streamflow. For bores within 10 km of major streams, 13% have a high correlation (defined as >0.8) and 94% have a positive correlation. For bores >10 km from the major streams, none have a high correlation and 86% have a positive correlation. Note that the small negative correlations recorded at some groundwater-monitoring boreholes are generally not statistically different from zero.

High-frequency stream and groundwater monitoring

Figure 9*a* shows the head measurements for a period of 6 months of pumping activity and surface-water and groundwater monitoring (October 2007–April 2008). The monitored period shows features of groundwater withdrawal at low river flow, dam releases (starting mid-December and mid-January), and floods (peaking end of December and in early February). Pumping durations during the irrigation season are shown in Fig. 9*b*. A clear and rapid response of >1.5 m drawdown to this pumping is seen in the deeper, semi-confined aquifer (borehole 3–2). In the shallow phreatic borehole (borehole 1) closer to the river, a much smaller response is seen; however, changes are still clearly correlated with the pumping. Both borehole locations also show rapid responses to changes in the river level from both dam releases and the floods (Fig. 9*a*). However, how much of this is related to a transient pressure loading response or to real groundwater recharge is presently not known. Figure 9*c* shows a time-series of the vertical gradient between the shallow and deep piezometers at borehole 3, which was zero or downward for the entire period. In Fig. 9*d* the gradient between the river and the upper aquifer and the river and the lower aquifer has been calculated. In both cases, except for very short periods of time, there is a gradient from the river to the aquifers, steeper for the case of the lower aquifer. Furthermore, the cumulative water flux between the river and the upper aquifer has been calculated using a transmissivity of 200 m^2 day^{-1} (from an unpublished aquifer test) (Fig. 9*e*). This calculation shows that during the monitoring period the river is losing overall, and only very slightly gaining during low river flow, when there are no nearby groundwater withdrawals. This is also illustrated by the representative water level profiles in the vertical cross-section of the site (Fig. 10).

Discussion

Towards a new equilibrium

The shape of the decline curve in the groundwater hydrograph plot depends on the type of aquifer from which the groundwater is being withdrawn and the rate of withdrawal (Fitts 2013). In a homogeneous aquifer when there is constant withdrawal, groundwater is initially removed from storage and the zone of depressurisation gradually extends away from the point of pumping (Fitts 2013). In nearby groundwater-monitoring boreholes the groundwater level initially falls rapidly. After a period of time, which depends on the hydrological properties of the sediments, the rate of decline will slow and the groundwater level will asymptotically approach a new equilibrium. This is represented by the curve labelled 'A' in Fig. 11. If there is a linear increase in withdrawals the groundwater level declines linearly (curve type 'B' in Fig. 11). If there is an exponential increase in withdrawals, then initially there will be a slow decline and then after some years the water level in the monitoring borehole will decline rapidly (line type 'C' in Fig. 11) (Soeder *et al.* 2007).

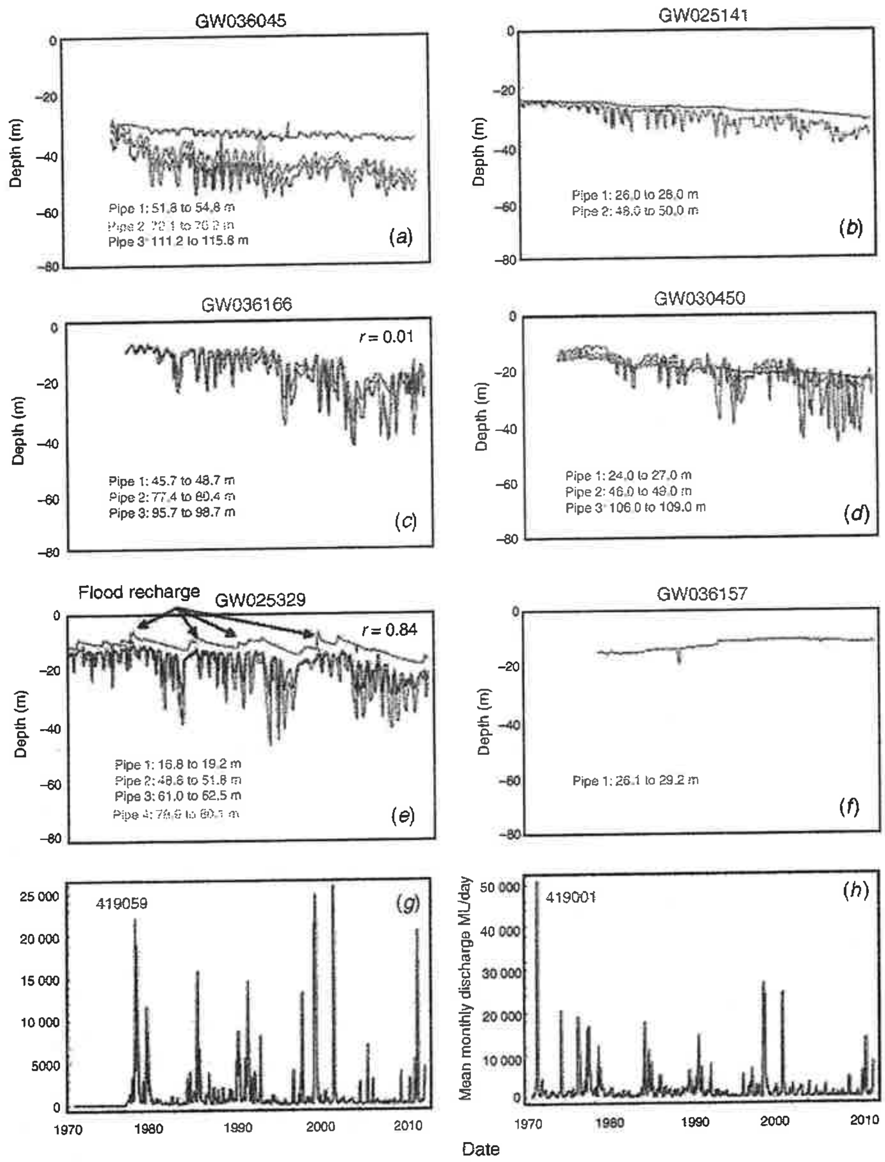


Fig. 4. Representative groundwater and streamflow hydrographs from the Namoi Catchment: (*a*) initial rapid decline followed by a plateau in the rate of decline indicating near constant pumping and a new equilibrium being reached; (*b*) linear decline, indicating linearly increasing withdrawal; (*c*) exponentially increasing withdrawal impacts, followed by recovery; (*d*) groundwater head reversal between the upper and lower portions of the aquifer system; (*e*) flood recharge; (*f*) rising groundwater level; (*g*) Namoi River streamflow record correlated with GW025329 (r = Pearson's correlation coefficient for the paired cumulative streamflow departure and de-trended groundwater time series); and (*h*) Namoi River streamflow record correlated with GW036166. The locations of the monitoring points are shown in Fig. 1.

All three styles of declining groundwater level are observable in the Namoi Catchment aquifers. The measured groundwater level recorded in a monitoring borehole reflects the superposition of the effects from multiple points of withdrawal and cumulative recharge contributions; thus, the idealised curves, shown in Fig. 11, are not usually observable. However, the gross trends can be seen.

Dynamic equilibrium due to groundwater withdrawals can be defined to have been reached when the impacts in one year are the same as in succeeding years (Kendy and Bredehoeft 2006). The time required for an aquifer system to reach a state of dynamic equilibrium depends upon the hydraulic characteristics of the sediments and the distances from the irrigation bore to the river and flood recharge zones. The groundwater level curves in Fig. 4*a* for the intermediate (blue) and lower (green) semi-confined aquifers are representative of type A decline due to constant pumping. It took 15 years for the rapid decline to stabilise; however, equilibrium has still not been reached after >40 years of withdrawals, as is evident from the continuing subtle decline. It is apparent in Fig. 4*a* that there is little leakage between the

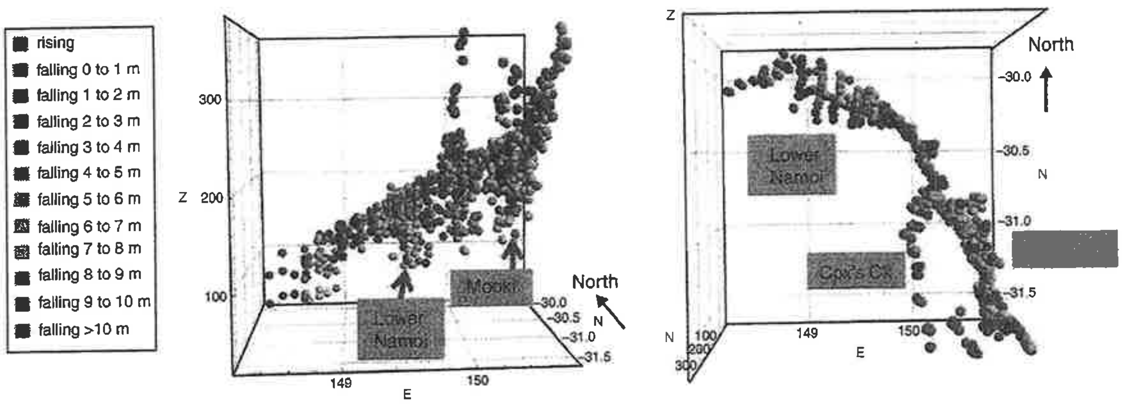


Fig. 5. Groundwater level trends between 1988 and 2008. Each point is plotted at the midpoint of the slotted intervals in the groundwater-monitoring pipe: left, side view; right, overhead view. (Units: latitude, longitude, and elevation (z) m AHD).

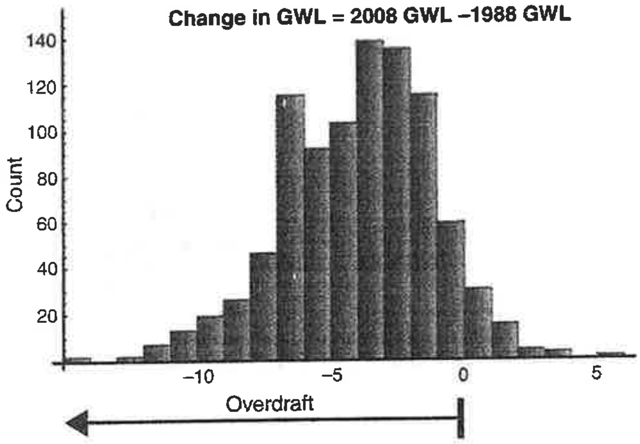


Fig. 6. Histogram of the change in the groundwater level (GWL) between 1988 and 2008 for all monitoring locations in the Namoi Catchment.

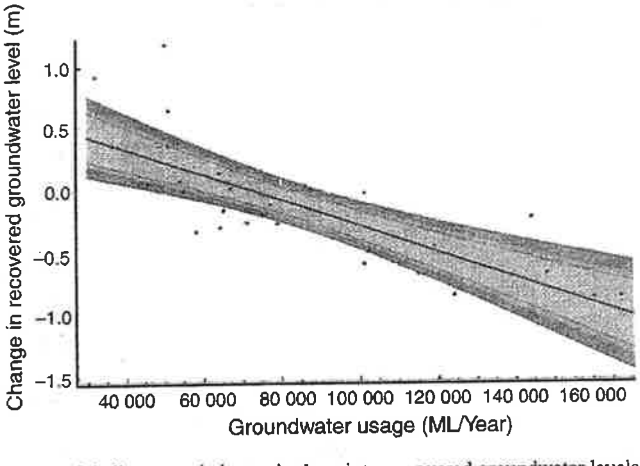


Fig. 7. Median annual change in the winter recovered groundwater levels *v.* groundwater usage recorded throughout the lower Namoi Catchment between 1978 and 2008 (90%, 95%, and 99% confidence interval bands shown in green, blue, and purple, respectively).

overlying unconfined aquifer (red) and the underlying semi-confined aquifers at this location.

The groundwater levels in hydrograph set Fig. 4*b* display nearly linear declines over the period of measurement. Linear declines in the groundwater level can be attributed to an increase in withdrawal with time, which prevents the system from reaching a new equilibrium. At this location, the decline is not due to the impact of a single, nearby pump; rather, it is the result of the superposition of many withdrawals from across the region.

Throughout the Namoi Catchment, there are no examples of type C (continuous, exponentially increasing withdrawal) from the beginning of monitoring until present. However, hydrograph set Fig. 4*c* is an example of exponentially increasing withdrawal at all levels of the aquifer system for the first 30 years of measurement. The similarity of the curves highlights the good vertical connectivity at this location (this connectivity may be natural via well-connected sand and gravel sheets, or due to the way the monitoring pipes were installed). Since 2004, there has been a partial recovery in the groundwater level.

The 3D plot of the change in the recovered groundwater levels, for the period 1988–2008 (Fig. 5), highlights the large degree of variability in how the aquifer systems of the Namoi Catchment have responded to groundwater withdrawals and variable recharge. Large areas of aquifer overdraft have occurred in the Mooki, Cox's, and lower Namoi Catchments. The largest declines in groundwater levels have occurred in the lower, semi-confined aquifers; the groundwater level in these aquifers has fallen by greater than 10 m. Such large declines are isolated, as shown in Fig. 6, which highlights that the groundwater level in the majority of the monitoring boreholes has fallen 1–7 m. The extent of the impact of the groundwater overdraft is shown in Fig. 7, which is a plot of the median annual change in the winter recovered groundwater levels *v.* groundwater usage recorded throughout the lower Namoi Catchment between 1978 and 2008 (the subcatchment with the longest groundwater level record, highest frequency of floods, and largest area of irrigated agriculture in the Namoi Catchment). This plot is used for the Hill Method of determining the 'safe yield' of an aquifer (Sophocleous 1998). We note that due to the groundwater monitoring boreholes being concentrated in the region of the irrigation bores, there is a bias towards sampling pumping-

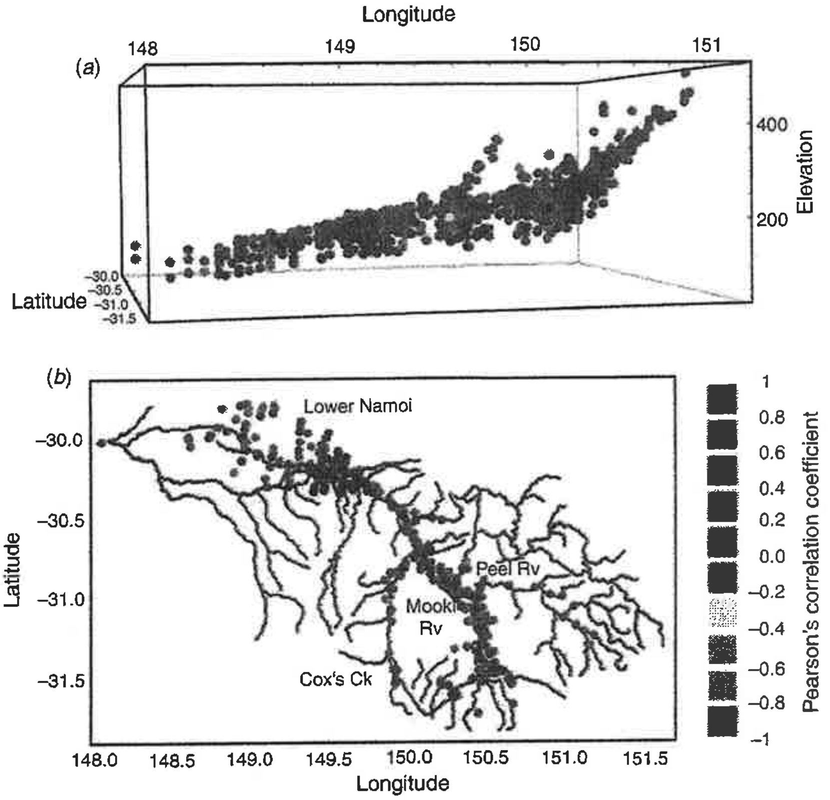


Fig. 8. Pearson's correlation coefficient (r) for each pair of cumulative streamflow departure and de-trended groundwater time-series (red, strong positive correlation; green, weak or no correlation; dark orange, strong negative correlation). (a) East–west 3D view of the colour-coded correlation indices. Each point plotted at the midpoint of the borehole slotted interval. (b) Map of the colour coded correlation indices. Points shown in the map are for the shallowest measurement, usually the unconfined aquifer. (Units: latitude, longitude, and elevation (z) m AHD).

influenced areas of the catchment. However, this plot highlights that for most years, more water has been withdrawn from the aquifer systems than is offset by recharge. The existing Water Sharing Plan has set a sustainable yield (locally called the diversion limit) of 86 000 ML year^{-1} (NSWG 2008; DWE 2009). Figure 7 indicates that under this rate of withdrawal the groundwater level will fall (90% confidence interval), which is to be expected given that groundwater hydrographs in Fig. 4a, b, and d indicate that dynamic equilibrium has not been reached. The sustainable-yield groundwater flow modelling undertaken by CSIRO (2007) indicates that under some climatic scenarios dynamic equilibrium will not be reached within 111 years. Thus, the Namoi Catchment Action Plan 2010–2020 (NCAP 2010) goal of not allowing the groundwater levels to fall cannot be achieved without reducing groundwater withdrawals, or changing the way both surface-water and groundwater are distributed and used throughout the whole of the Namoi Catchment.

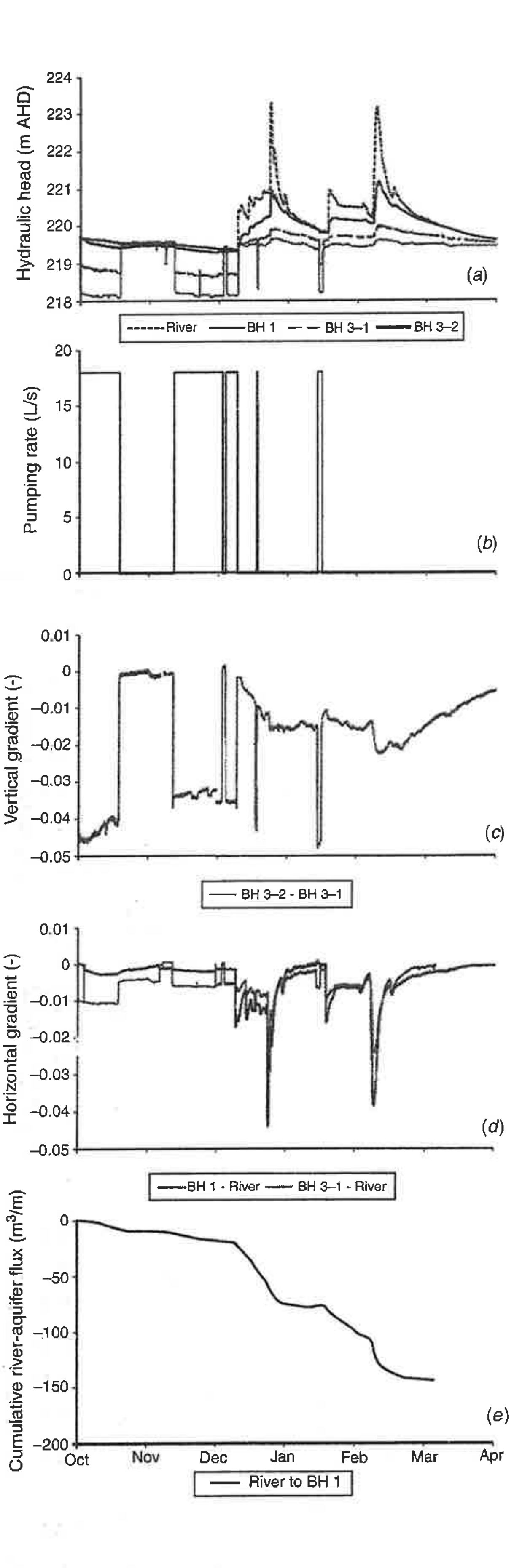
In regions where there has been a large fall in the groundwater level (Fig. 5), the downward movement of salts may have been induced (Acworth and Timms 2009). Further research is also required to quantify the extent of salt movement caused by groundwater withdrawals.

Although there has been a clear trend of falling groundwater levels since the beginning of the groundwater withdrawals in the 1960s for the majority of the Namoi Catchment (Figs 4 and 5), there are isolated places where the groundwater level is rising. Between the Namoi River and Burren Junction, a cluster of groundwater hydrographs displays a slight rise in the groundwater level. Most rises are <1 m, but they can be as high as 2 m (Figs 4f and 5). In this region, there are limited groundwater withdrawals. The rising water levels are probably due to a combination of factors, including leakage from on-farm dams, deep drainage beneath irrigated crops, and the removal of large eucalyptus trees. The exact contribution of each factor is unknown.

There is a need to better understand the impact of rising groundwater levels in the headwaters of all catchments, and in the south-west of the lower Namoi Catchment (Fig. 5). This may have future ramifications for the mobilisation of salts in the near-surface soils.

In the lower Namoi Catchment between 1988 and 2008, there was a system-wide increase of groundwater levels of >0.25 m in only 4 years (Figs 6 and 7). These correspond to the wetter growing seasons 1994–95 and 1996–97, and flood years 1998 and 2000.

In a few locations there has been groundwater head reversal between the upper and lower portions of the aquifer system. The initial higher head in the lower semi-confined aquifer is due



to upward pressure from the underlying Great Artesian Basin (SWS 2012; N. Merrick, pers. comm.). When the semi-confined aquifer is depressurised, the groundwater level in the semi-confined aquifer-monitoring borehole falls faster than in the overlying unconfined aquifer. This can be observed in Fig. 4*d*.

Water movement between streams and aquifers

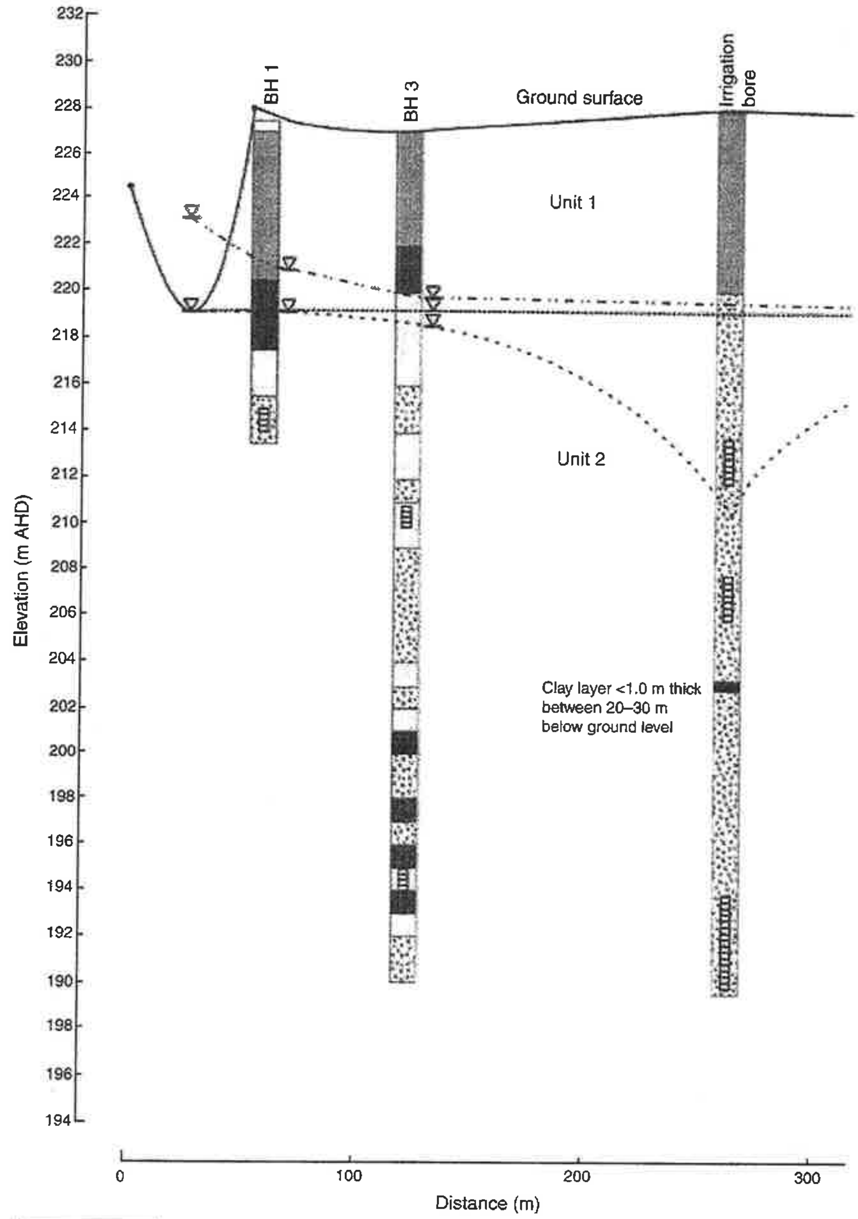
Between Narrabri and Wee Waa there is a cluster of monitoring pipes near the Namoi River that are hydraulically connected to the floodwater recharge zones (Kelly *et al.* 2009; Blakers *et al.* 2011; Lamontagne *et. al.* 2013). Figure 4*e* is typical of such groundwater hydrographs where there is good flood recharge. Between floods the groundwater level slowly declines, and the yearly pumping drawdown increases from year to year in the semi-confined aquifers; this reflects the reduction in the amount of water in storage throughout the pumping capture zone. A strong correlation between floods and the groundwater level is observable by comparing the peaks in the groundwater hydrograph Fig. 4*e* and the nearby streamflow hydrograph Fig. 4*g*.

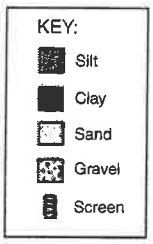
Throughout most of the lower reaches of the Mooki River, Peel River, and Cox's Creek, and the Namoi River from Boggabri to south of Burren Junction, there is a strong association between streamflow and groundwater level for the unconfined aquifer monitoring boreholes within 10 km of the streams or rivers (Fig. 8). The proportion of the groundwater-level rise that is due to loading *v.* actual recharge cannot be determined from the time-series analysis (van der Kamp and Maathuis 1991; Maliva *et al.* 2011). The results suggest that there is an opportunity to enhance recharge with a series of weirs. However, we acknowledge that this may have implications for streamflow and river ecology.

There was poor correlation between streamflow and the measured groundwater levels in the upper reaches of all rivers and streams, probably due to the low number of streamflow-gauging stations in these regions. There is also poor correlation between streamflow and the groundwater levels in the northern and western portions of the lower Namoi Catchment. This is most likely due to the distance between the Namoi River and the monitoring boreholes (>10 km); thus, the potential groundwater level changes from dam releases and floods are significantly dampened in these regions (Kelly *et al.* 2009, 2012).

The high-frequency monitoring of surface-water and groundwater near the riverbank of the Namoi River shows a dynamic response to both floods and groundwater withdrawal (Figs 9 and 10). It could be argued from these data that the

Fig. 9. High-frequency (15 min) monitoring of stream and groundwater levels on the bank of the Namoi River between October 2007 and April 2008 at the detailed study site in the Maules Creek subcatchment (see Figs 1 and 3). (*a*) Elevation of river and borehole hydrographs; (*b*) pumping rates and periods in the irrigation bore (Fig. 3); (*c*) time-series of the vertical hydraulic gradients between the upper unconfined aquifer and the lower semi-confined aquifer. A negative value indicates a downwards gradient. (*d*) Horizontal hydraulic gradients between the river and the unconfined aquifer (borehole 1), and the river and the semi-confined aquifer (borehole 3). A negative gradient indicates a gradient from the river towards the aquifer. (*e*) Time-series of cumulative nominal fluxes between the river and the unconfined aquifer.





Observed water levels

Line	Case	Date	Description
···············	1	12/11/2007	No flow event, No pumping
· · · · · · · ·	2	12/11/2007	No flow event, Pumping
-- -- -- --	3	24/12/2007	Flow event, No pumping

Fig. 10. Cross-section from the Namoi River through observation boreholes 1 and 3 to the irrigation bore (see Fig. 3 for locations). The different times for the water-level profiles are shown in the hydrographs (Fig. 9*a*).

response of the shallow groundwater near the river due to pumping is not obvious, due to the existence of low-permeable units between the shallow river alluvium and the irrigation bore (Fig. 10). However, there is evidence of a small response in the shallow alluvium, which, together with the development of increased vertical downward gradients, indicates that a long-term, sustained leakage could be induced from the upper aquifer, thereby indirectly affecting the river flows. This sustained and potentially substantial long-term recharge from the river into the aquifer was also seen in studies of the Namoi River in the Maules

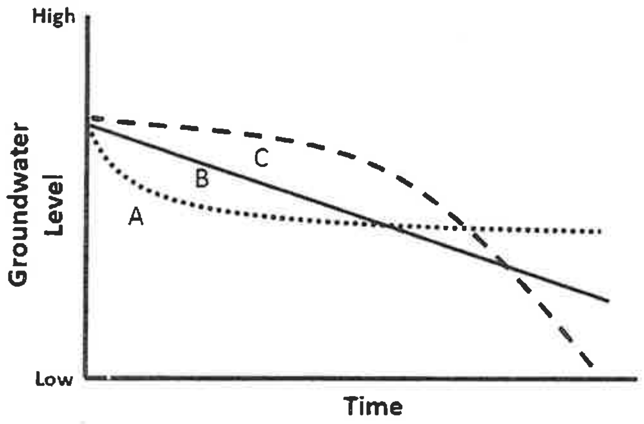


Fig. 11. Idealised drawdown for an aquifer system by one or more pumping bores: (*A*) constant withdrawal, (*B*) linearly increasing withdrawal rate, and (*C*) exponentially increasing withdrawal rate (adapted from Soeder *et al.* 2007).

Creek subcatchment by Andersen and Acworth (2009), Giambastiani *et al.* (2012), and McCallum *et al.* (2013*a*, 2013*b*).

River recharge may further increase in the future if the current groundwater extraction level is maintained. The slow leakage from the upper to the lower aquifer, observable in Fig. 9, means there is a delay in the impact of the groundwater withdrawal on the surface-water resource. Such delays pose a challenge for water-management policies that are based on monitoring sustainable surface-water indicators in the present.

Furthermore, the change in the direction of water exchange between river and aquifers may have severe impacts on the river flow during prolonged drought periods where the losing conditions may affect the river's resilience to drought (i.e. the ability of a sustained natural groundwater discharge in providing baseflow through drought periods; McCallum *et al.* 2013*a*). The full ecological impact of the loss of this resilience is yet to be seen.

Groundwater management challenges

Balancing ecological management goals in a catchment where groundwater is a major resource is a difficult challenge. As shown by the multi-decadal, catchment-scale analysis of groundwater level, aquifer drawdown is greatest in regions remote from the river, whereas the small-scale study of pumping impacts demonstrates the immediate influence on groundwater levels due to pumping near the river.

The time to impact from bores $\geq$20 km away from the groundwater-dependent ecosystems in the corridor near the Namoi River is in the order of decades (Sophocleous 2012). Applying groundwater-level thresholds with reference to historical groundwater levels will not achieve the goal of protecting or improving the groundwater-dependent ecosystems in the river corridor within 10 years. By contrast, bores within 1–2 km of the river have been demonstrated to have a measurable short-term impact on streamflow, and must capture some of the recharge that would otherwise migrate to the more distal portions of the catchment. These bores are unlikely to trigger threshold reductions, because when it floods the groundwater level in the river corridor recovers.

Today there is consensus that groundwater-dependent ecosystems should be protected, and in places remediated. This is clearly reflected in the threshold goals of the Namoi Catchment Action Plan 2010–2020 (NCAP 2010). It is apparent from the results presented here that there is a need for local area management of water within the context of the regional Water Sharing Plans and Catchment Action Plans. The semi-confined aquifers of the central portion of the Mooki Catchment and the western and northern portions of the lower Namoi Catchment are poorly connected to the river and flood recharge pathways, as indicated by the large drawdowns in these regions and the lack of a response to floods. Continued pumping in these regions, at volumes close to those allocated under the active Water Sharing Plan (NSWG 2008), must cause the local groundwater level to fall further, because the groundwater systems at these locations have not yet reached a new dynamic equilibrium.

Aquifers store water in an evaporation-free environment, and as discussed by Bredehoeft (2011), there can be an advantage to using groundwater remote from the river. It provides an insurance against drought, and if used when there is low flow in the river, it can delay the impact of using groundwater on the riparian corridor. During wet periods, the use of groundwater from bores far from the river can be replaced by sourcing water supplies from boreholes near the river or directly from the river. Groundwater is an important source of water for irrigating crops, but if groundwater is allocated and managed only in the context of point of use, or in assumed isolation from surface-water, sustainable access to groundwater for all existing irrigation farms will be difficult to attain while minimising the impact on groundwater-dependent ecosystems. This will only be achieved if surface-water and groundwater are managed as a single resource at the catchment scale. In conjunctive water-use plans, consideration needs to be given to the response time between the point of groundwater withdrawal and points of impact. The time to the establishment of a new dynamic equilibrium due to groundwater withdrawals needs to be considered in water-management policies and plans. The fundamentals of groundwater hydraulics were mostly well understood in the early 1900s, but as highlighted in this case study, further research is required on how best to balance the use of groundwater and surface-water to support irrigated agriculture, while protecting groundwater-dependent ecosystems.

Conclusions

When groundwater resources are initially developed, the water is mined from storage. In the Namoi Catchment it took two decades from the start of pumping before there were sufficient data to enable the mapping of pathways of connectivity, and to allow an assessment of the impacts of groundwater withdrawal in a complex sedimentary setting. An analysis of both groundwater and streamflow hydrographs shows good hydraulic connectivity throughout the unconfined aquifer system extending up to 10 km perpendicular to the Namoi River. Beyond that distance, there is little or no discernible streamflow/flood recharge signature in the groundwater hydrographs detected from signal correlation.

The detailed high-frequency stream-level and groundwater-level monitoring showed that the stream-and-aquifer interactions are highly dynamic and change rapidly with the onset of groundwater pumping, during flooding, and with water releases from upstream dams. This highlights that, to get a better understanding of these processes, we need more dedicated monitoring at a higher frequency along other reaches of the river network. At the site investigated, the impact of the groundwater withdrawal on the streamflow was delayed by the presence of aquitards between the deeper aquifer, from which the water is being sourced, and the shallower aquifer that is directly connected to the river. However, the reduced heads in the lower aquifer will eventually lead to a depletion of the river baseflow. On a wider catchment scale, this has caused the Namoi River in the Maules Creek subcatchment as well as other areas to change from gaining to losing as a direct consequence of the groundwater withdrawals used in irrigated agriculture over the last decade. One of the primary results from this research is the extent to which the Namoi River has switched from gaining to losing water, and this supports and extends the findings of Giambastiani *et al.* (2012) and McCallum *et al.* (2013*a*).

The results presented in this paper show that further research is required on the delivery and usage of water, at different times and to different locations, to achieve both goals of supporting irrigated agriculture and protecting groundwater-dependent ecosystems. This can be more readily achieved if surface-water and groundwater are managed as a single resource at the catchment scale. We now have enough knowledge of the effects of groundwater withdrawals and their impacts on groundwater level, and on stream-and-aquifer interaction. This facilitates research opportunities on optimising the conjunctive use of surface-water and groundwater, while considering the ecological impacts.

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