Groundwater Knowledge and Gaps in the Condamine Alliance Area

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Executive Summary

This document captures our current understanding of groundwater quality, quantity and interaction with rivers in the Condamine Alliance Area. The purpose is to clarify groundwater related research priorities relevant to the Cotton Catchment Communities CRC and Condamine Alliance. The scope is limited to reviewing available information. Although many investigations have been undertaken in the past within the region there are still many gaps in our understanding of groundwater. This limits our capacity to manage how water is allocated (between all stakeholders, including rural, mining, energy production, urban users and the environment) and to understand salinity risks. To allow for an informed discussion on these issues, improvements are needed in the underlying science.

Estimating catchment scale water balances is not an exact science. There are uncertainties in estimating rainfall recharge, river recharge, irrigation returns to the aquifer, inflows through basement rocks, discharge via the rivers, evapotranspiration losses, surface water storage losses, and quantifying flood events. This is why catchment water balances have to be modelled and estimates given (ideally with confidence intervals). Through improved measurement techniques, higher resolution data and advances in numerical computer modelling techniques, the errors associated with quantifying water fluxes through the catchment can be reduced and water management decisions improved. In some cases the quality of the data can be improved easily, for example, by increasing the density of rainfall gauging stations, and recording bore water levels more than 4 times per year where more rapid changes occur. In contrast to these quarterly bore measurements, in the USA bore water levels are reported on the web daily for over 4000 wells throughout the country.

There are many unanswered questions about the extent of interaction between surface and ground waters, and the long term trends on water quality and the impacts on the environment. Although considerable work has been undertaken in the past this work has not been systematic with respect to groundwater quality.

Current water balance models need to be updated. In particular, there needs to be improved modelling of surface and ground waters as a connected resource. This has significant implications with respect to current management practices which separate surface and ground waters. An enhanced understanding of the interactions between rivers and aquifers would help in determining what water management decisions need to be made in order to achieve current environment goals and end of valley targets.

Listed below are recommended projects that will advance our scientific understanding of the aquifers in the Condamine Alliance Area and would help with benchmarking conditions for future groundwater resource plans and understanding salinity and water quality.

- Record irrigation deep drainage at the shallow water table.

Better estimates of irrigation deep drainage are needed and then these estimates should be incorporated into regional surface and ground water balance models explicitly. Current deep drainage research is focused on how much water passes the root zone. In addition to this, we need measurements of the shallow water table response throughout the growing season. We need to know how much water reaches the shallow groundwater systems and then how much reaches the deeper aquifers that are used for irrigation or moves laterally through the vadose zone and shallow aquifers.

At the moment irrigation deep drainage is not considered as a separate input in aquifer water balance models of the Condamine Catchment, so any irrigation deep drainage that is reaching the aquifers in current models is being accounted for through adjustments in other variables. Barrel lysimeter measurements under furrow irrigated crops indicate that
approximately 10% of the irrigation water used throughout the growing season goes to deep drainage. A quick calculation for the Condamine Catchment shows that this is a significant gap in our understanding of the water accounting. Assuming 30,000 hectares of irrigated cotton (The Australian Cottongrower, 2006) and if 4.3 ML/hectare of irrigation water is used (Goyne et al., 2000) and 10% of the irrigation water goes to deep drainage throughout the irrigation season then 13,000 ML of water migrates downwards towards the shallow aquifers. To put this volume of water into perspective, this is the same order of magnitude as some of the reported average recharge estimates for Condamine alluvial aquifers. Before this recharge component is added to any catchment water balance models more work is needed because we do not know how much of this water recharges the shallow water table and then the productive aquifers, nor do we know what time lag there is between irrigation and potential shallow aquifer recharge. Also, we do not know if it is appropriate to scale between point measurements of deep drainage at a limited number of sites to regional scales. This is a significant gap in our understanding.

- Investigate the moisture status (moisture content and potential) of the unsaturated zone below the root zone, to determine how deep the drained water has penetrated under irrigated areas.

  The deep drainage could still be filling a historic water deficit in the unsaturated zone and is therefore not yet appearing as groundwater recharge. This would help to resolve the issue discussed above.

- Build an interactive 3D geological property model of the hydrogeology of the Condamine Catchment to gain insights into physical processes, show river and aquifer connectivity, and provide an enhanced framework for management and communication.

  Most petroleum basins, mines and many industrial contaminated sites have had interactive 3D geological property models constructed to display all the data known about the area of interest. From the information reviewed for this report there are enough data to be able to build a 3D model of the surface and ground waters of the Condamine Catchment.

  This would provide an important aquifer management tool, coordinating all sources of data and would help with communicating groundwater issues in public forums.

  A 3D time lapse model of the decline of the major alluvial aquifer would be an important communication tool, and would help focus the discussion on future water allocation. Also where the water table is rising it would help with understanding the processes driving dryland salinity outbreaks.

- Map recharge and discharge zones along the rivers and streams.

  Floating geophysical surveying along the Condamine River using a combination of temperature and electrical resistivity imaging would highlight priority areas for more detailed investigation. Electrical resistivity imaging provides information on the thickness of clay, sand and gravel layers, and changes in water conductivity that may indicate recharge and discharge zones. This work would complement the goals of managing connected water resources and conjunctive water management (IAH, 2004 and Fullagar, 2004).

  Recently Baskaran, Ransley and Brodie from the Bureau of Rural Sciences have tested a number of approaches including seepage meters, ecological indicators, hydrographic
analysis, hydrometric analysis, near surface geophysics, remote sensing and hydrochemical methods (including major ion, isotopes, radon and chlorofluorocarbon) for mapping surface and ground water interactions. The results of their investigations should guide which methods would be likely to yield cost effective results.

- Incorporate farmer recorded rainfall data into water balance models.

The rainfall gauging network used by the Bureau of Meteorology for recording rain is too coarse for local scale catchment water balance modelling, resulting in substantial uncertainty in the rainfall contribution. Incorporating reliable farmer recorded rainfall data into the regional water balance model would reduce this uncertainty. This is particularly important near the catchment boundaries where there is orographic rainfall and recharge zones for the alluvial aquifers, but very few nearby rainfall gauging stations.

- Develop a best practice approach to water allocation modelling.

Many of the alluvial aquifers within the Condamine Alliance Area are being mined. If the aquifers are to be used in a viable manner then usage will need to be reduced in some areas. Any changes to usage need to be based on the best available science. To date the modelling of the available yield from the aquifers within the region has been too simple and should be improved to better inform any alterations in allocation, and to enhance our understanding of aquifer flux dynamics. An extensive new connected surface and ground water model is required. The representation of the aquifers in a new catchment water balance model also needs to capture the complexity of the alluvial sediments.

Groundwater licence holders want to know that the best available approaches have been used for determining the available yield of the aquifers, and that the uncertainties in the allocated volumes are characterised. The best available approach now is to use coupled surface and ground water modelling.

It is now possible to couple surface and ground water modelling using several commercially available software packages. Queensland Department of Natural Resources and Water (QLD NRW) has already applied this approach in coastal regions, but not in catchments of interest to the Cotton Catchment Communities CRC or Condamine Alliance. A MODHMS model of the region would update the water balance modelling to current best practice levels.

- Compare cumulative rainfall departure data with QLD NRW monitoring bore hydrographs.

A comprehensive statistical analysis is needed comparing rainfall trends to groundwater behaviour. From this analysis index maps can be developed to determine where aquifer behaviour is in or out of sync with respect to prevailing climatic conditions. A long range allocation predictive tool can also be developed from this analysis by linking into long range forecast tools, the Southern Oscillation Index and Pacific and Indian Ocean temperature and pressure indices.
• Allocations need to be linked to the recharge potential under changing climatic conditions.

Based on the research undertaken in the above two projects further research needs to be carried out on how to convey to the community the links between the long term rainfall trends and aquifer behaviour. Water allocation modelling can only be calibrated against historical data, but future recharge may not equate to past recharge (it may be more or less). Recharge to the Condamine River alluvial aquifers is extremely variable so to allow for better future planning the variability of the available water needs to be captured in the way groundwater is allocated. Therefore groundwater usage needs to be linked to the long term probability of recharge, with a community agreed acceptable error if the aquifer is to be used in a viable manner.

• Measure the trends in water salinity and ionic chemistry from irrigator bores.

Saline water overlies and is adjacent to the fresh water intervals used for irrigation water. Some of this saline water approaches salinity levels that would reduce crop yields if used. Under heavy pumping and in areas where aquifer head is declining, the saline water is possibly moving towards the fresh water zone. We have limited understanding of the rate of migration of the saline water. We need to understand how irrigation bore water quality changes throughout the season and over the long term.

• Systematically measure trends in water salinity and ionic chemistry using the QLD NRW groundwater monitoring network.

A trend analysis of the QLD NRW groundwater quality data is needed, preferably after a new round of sampling. Measuring water salinity using the QLD NRW groundwater monitoring network bores is a larger project compared to using irrigator bores because each monitoring bore needs to be pumped prior to taking measurements.

• The surface and ground water chemistry of the Condamine River and tributaries needs to be systematically studied at a local scale.

Major ion and isotope chemical evolution studies need to be updated along the Condamine River and tributaries. Data from the soft and hard rock regions are needed as part of these investigations. The water chemistry also needs to be analysed with respect to long-term soil health and crop yields. Aspects of this have been undertaken by McNeil and Horn (1997), but it needs to be expanded along the lines of the work undertaken by Lavitt (1999) in the Mooki catchment, Liverpool Plains, NSW.

There is a substantial water chemistry data set that has been collected by QLD NRW over the last 3 decades, but as far as could be ascertained an up to date comprehensive analysis has not been undertaken.

• Couple the groundwater chemistry to the groundwater flow modelling.

To better understand the migration of zones of saline groundwater towards the fresh water zones, the water chemistry needs to be coupled to the groundwater flow models. However, in order to be able to couple the water chemistry to the groundwater flow modelling a higher resolution MODFLOW, FEFLOW or MODHMS model of the catchment needs to be constructed. Higher resolution models are required to capture the geological complexity of the aquifers.
• The hydraulic interaction between the coal seam gas units and the overlying alluvial sequences needs to be investigated.

Drawdown in the coal seam gas aquifers may affect other aquifers. Also there may be issues with the disposal or use of the coal seam water.

• Develop a correction for sediment load on river electrical conductivity measurements.

A correction is possibly needed for the sediment load in the river water when measuring electrical conductivity to determine river salinity and salt load levels. At the moment no correction is being made for high cation exchange capacity clays in the water. These clays could be contributing to the electrical conductivity of the water, resulting in the overestimation of salt loads.

• Evaluate the extent of aquifer subsidence

In the areas of the largest declines in groundwater head the decline is of a magnitude that suggests there is significant potential for aquifer subsidence to occur. It is recommended that the extent of potential subsidence be evaluated by baseline ground level survey with supporting modelling.
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1 Introduction

Groundwater is an important source of water for many sectors in the Condamine Alliance area (Figure 1) including irrigated agriculture, stock and domestic water supply, mining, energy production and urban uses. Groundwater also has an important ecological role both underground and as a baseflow component for the streams and rivers of the region. There are 3533 groundwater authorisations in the area (Free, 2003). A balance needs to be found for all sectors dependent on groundwater extractions so that the region can flourish economically, while the environment is maintained or improved.

In order to reach a balance between groundwater usage and acceptable influences on the surrounding environments we need to have extensive knowledge of the hydrogeology of the Condamine River and tributaries. This scoping study aims to describe the extent of our knowledge about the hydrogeology and to determine priority areas of research for the Cotton Catchment Communities CRC and Condamine Alliance. Similar reports have been prepared for the other catchments where cotton is grown in the Darling Basin. The scope is limited to reviewing available information. This report describes:

- how well current conditions are benchmarked,
- where groundwater extraction is causing significant declines in groundwater heads,
- where irrigation returns (deep drainage) are causing the water table to rise,
- how the aquifers interact with the rivers and streams,
- how water chemistry is changing throughout the aquifer,
- what we know about aquifer recharge,
- the status of the groundwater models within the Condamine alluvial aquifers, and
- how we can reduce the uncertainty in determining the available yield from aquifers.

Figure 1. Condamine Alliance Area (CA, 2004).
Many of these concerns have been raised and explored in the Pratt Water Report (2004). The fact that this was for the Murrumbidgee area shows that the concerns are not unique to any one catchment, but apply to all catchments where groundwater is extracted and extensive surface irrigation is undertaken.

Water allocation is subject to Water Resource Plans and needs to be based on good quality data and rigorous scientific estimates of the available yield of the aquifers (“available yield” is used to encompass aspects of the concepts of both sustainable yield and safe yield with water quality and ecological considerations). Estimating the appropriate usage of groundwater is not an exact science, as it would be prohibitively expensive to measure accurately all of the inputs and outputs of the water balance. But as cheaper measurement methods become available, better record keeping procedures are adopted and better modelling systems developed, available yield estimates can be improved. There is no universally accepted method for determining the appropriate extraction limit for an aquifer. Aquifer water balance modelling using packages like MODFLOW or FEFLOW can help with the quantification of the water balance and allow for various usage options to be explored. But, the final usage figure has to balance various social goals ranging from mining of groundwater resources through to minimising groundwater extractions for environmental concerns.

How farming, mining, energy production and urban water use practices are managed is an integral part of achieving aspects of these catchment management objectives. In particular, the use of groundwater by all sectors is one aspect where extraction at a single point in the landscape can have a significant impact on an area of the catchment larger than the extent of the surface land holdings and its associated bores.

The benchmarking of current conditions is critical for understanding research priorities. The research priorities listed in the Executive Summary and Conclusions attempt to fill the gaps in the characterisation of groundwater quality, our knowledge of the interaction between fresh and saline zones of the aquifers, our understanding of groundwater recharge and in reducing the uncertainty in the available yield of the aquifers. We need a better snapshot of present conditions in order to be able to reference any changes that may occur in the future.

This report focuses on groundwater from the alluvial sediments underlying the central portion of the Condamine Alliance area in the irrigation districts (Figure 2). Other aquifer systems, in particular the Main Range Volcanics (Basalts), provide significant quantities of good quality groundwater and require careful management, but are of less relevance to the cotton industry. Although the discussion below will often refer to the alluvial aquifer as if it is a single body it needs to be appreciated that the alluvial sequences in the valleys are complex in nature, consisting of many interconnected unconfined and semi-confined aquifers. Groundwater from the alluvial aquifers is an important component of the water supply for irrigated cotton. Despite the importance of this water supply there have been limited detailed investigations into groundwater dynamics and water quality. This report highlights the many gaps in our knowledge of groundwater conditions in the management of this resource.
Figure 2. Irrigation districts of the Condamine Catchment (Courtesy Condamine Alliance).
2 Hydrogeology Summary

Understanding the origin of the groundwater, its chemistry and its movement requires a comprehensive knowledge of the regional geology, both alluvial sediments and basement rock. The geology of the upper Condamine is generally well understood. A more comprehensive discussion is presented in Huxley (1982a, 1982b) and Skelt et al. (2004). Pearce et al. (2006) describe the hydrogeology of the Northeast Darling Downs (NE Downs), from Toowoomba north and west to the Condamine River. A simplified geological map of the catchment is shown in Figure 3 and cross sections in Figure 4.

The Condamine River and tributaries form the north-eastern headwaters of the Murray-Darling Basin. The east and south of the catchment are bounded by the Great Dividing Range. The Condamine River flows north-west from its headwaters near Killarney along the axis of a northerly dipping synclinal fold in the Clarence-Morton sub-basin. The western boundary, before the Condamine River turns west near Chinchilla, is the eroded Kumbarilla anticline ridge.

Sediments that form the major aquifer for the Condamine Catchment infill a valley eroded into Palaeozoic and Mesozoic sedimentary rocks and Tertiary volcanics. The basement rocks have an important influence on the water chemistry which is discussed further in Section 7. Along the southern, eastern and western margins of the catchments the sediments consist of colluvial sheetwash from the adjacent weathered hard rock regions. The majority of the central valley consists of alluvial sediments deposited by the Condamine River and its ancient forms. The sediments have a maximum thickness of 134m just south of Dalby and consist of meandering discontinuous random sequences of gravel, sands, silts and clays.

Alluvium in the headwater Condamine River tributary valleys consist of fine to coarse sand, gravel and boulders, reflecting the high energy depositional environment. These tributaries act as conduits recharging the alluvial aquifer of the Condamine River valley. In the tributary valleys the aquifers are unconfined, but further down gradient and moving northwards through the Condamine Catchment semi-confined boundary conditions are often encountered during pumping.

A mixture of fractured uplifted Jurassic sedimentary rocks and Tertiary Volcanics form the north-east boundary and Tertiary Volcanics, predominantly basalt, form the south-east boundary. Rainwater that infiltrates through the fractures in these hard rock regions is a minor recharge component for the unconsolidated sedimentary aquifers. Water from the western boundary fractured sedimentary rocks also contributes a minor amount of recharge to the unconsolidated sedimentary aquifer. The major sources of water to the unconsolidated sedimentary aquifers are believed to be continuous river losses and flood events (Lane 1979). Infiltrating rain across the broader plains is believed to be a minor contribution to recharge. Recent estimates of deep drainage under irrigated crops suggest that this may be a significant contribution to recharge, but irrigation deep drainage is not accounted for in current water balance models. However, the deep drainage may be filling a historic soil moisture deficit in the unsaturated zone.

Pearce et al. (2006) found gradients in groundwater levels in the NE Downs that indicate potential flow from the ranges in the east towards the Condamine River. Numerous 2D maps and cross-sections of the unconsolidated sediments and basement geology exist in Huxley (1982a, 1982b). All these data need to be coordinated into a 3D geological model of the region in order to advance our understanding of groundwater dynamics within the Condamine Catchment. A better 3D understanding of the unconsolidated sediments would allow for a more realistic 3D groundwater flow model to be constructed and the available yield of the aquifers determined.
Figure 3. Simplified geological map of the Condamine Catchment (modified from Power et al., 2005).
Figure 4. Schematic of the geology and groundwater chemistry displayed on cross sections moving northwards along the Condamine River (Huxley, 1982a).
3 Palynology

Palynology studies help with dating the age of the sediments and with correlating the unconsolidated sedimentary units between bores. A comprehensive palynology study can also help with determining the climatic conditions at the time the sediments were deposited and provide clues to the origin of stored salts.

Limited palynology investigations have been undertaken for the Condamine Catchment (De Jersey, 1973). Work similar to that undertaken in NSW by Martin (1979, 1981, 1991, 1994) or in the Lower Balonne by Macphail (2004) needs to be undertaken in the Condamine Catchment to help with constructing a comprehensive stratigraphic understanding of the colluvial and alluvial sequences.

4 Rainfall Gauging

Rainfall records are critical for the calibration of groundwater flow models. As will be discussed below, there is a strong link between the rainfall history and aquifer response. Therefore the quality of rainfall data used for water balance modelling is critical for determining available yields and environmental processes.

Within the Condamine Catchments, rainfall records are collected by the Australian Government Bureau of Meteorology (BOM) (http://www.bom.gov.au/hydro/wr/rge/). Within the Condamine-Culgoa catchments there are now 446 open rainfall stations. However, only 68 stations have rainfall records of 100 years or more.

QLD Department of Primary Industries and Fisheries produces the RAINMAN + STREAMFLOW CD that contains all the publicly available data on rainfall. Details on the CD can be viewed at the following web site: http://www2.dpi.qld.gov.au/rainman/

While the density of BOM rainfall gauging stations may be appropriate for regional forecasts it is too low for detailed surface hydrology or groundwater modelling. To improve the density of the rainfall data reliable farmer rainfall data sets should be processed with BOM records. This would improve the recharge and runoff estimates.

5 Groundwater Monitoring, Metering and Management

5.1 Groundwater Monitoring

Queensland Department of Natural Resources and Water (QLD NRW) maintains a network of 477 monitoring bores in the alluvial aquifers and 128 bores in hardrock aquifers throughout the Condamine Catchment (Free, 2003). Since 2003, 66 new monitoring bores were installed by QLD NRW under Murray Darling Basin Commission (MDBC) and National Action Plan (NAP) programs, mainly as part of the NE Downs project of Pearce et al. (2006). New monitoring bores are added each year for various water monitoring and research purposes. The distribution of the bores is presented in Figure 5. At each bore location one or more pipes have been installed to monitor various layers. Water levels from these bores form the basis of knowledge about aquifer heads and flow directions. The earliest monitoring network bores date from 1945, but most were installed throughout the 60s and 70s.
Islam (2006) graphed 100 of the hydrographs from the Condamine Catchment and three representative hydrographs are presented in Figure 6. Bore 422230057 located in the Cecil Plains area is an example where the aquifer is being mined - the water level has been declining since 1970 when monitoring began at this location. Bore 42230160 located near Dalby is an example where the aquifer started to be mined in 1990. Bore 42230164, 12 km east of Dalby and further from the main irrigation area is an example of where the water level is rising and may give indications of recharge rates where pumping is not affecting the groundwater.

To gain a snapshot of changes in monitoring bore water levels with respect to time it is common practice to subtract the recovered water levels of the bore from one year from water levels in the past. The recovered monitoring bore water levels are the levels recorded in July or August, before the beginning of pumping for the cotton growing season. Islam (2006) mapped the difference for 100 bores in the Condamine Catchment for monitoring bores where the depth to the water level was greater than 10 metres and the results are presented in Figure 7. The majority of the alluvial aquifer is being mined, with local pockets of groundwater level rise in the north and central east of the Condamine Catchment. Murphy (NRW, personal communication) mapped the change in water levels from 1967 to 2007 (Figure 8). The effects of groundwater pumping are reinforced by rainfall being lower than average since 1990 (Pearce et al., 2006; Dutta and Silburn, 2005).
Figure 6. Three representative hydrographs from the NRW monitoring network, in the Condamine Catchment, showing different aquifer head behaviours.
Figure 7. Change in water levels between 1980 and 2005 in monitoring bores, for bores deeper than 10m below the ground surface in the Condamine Alliance area (scale units metres; green indicates rising and red falling water levels) (Islam, 2006).
Figure 8. Change in water levels between 1967 and 2007 in monitoring bores, in the Condamine Groundwater Management Area (Greg Murphy, NRW, personal communication). The location of the Condamine Catchment groundwater management units is shown in Figure 9.
Groundwater models are calibrated against these bore hydrographs and the results are used as part of estimating the available yield. Presently, groundwater levels in the monitoring bores are recorded approximately 4 times per year, except in a small number of bores which have automatic recorders. Some of the hydrograph records date back to 1966 (Lane 1979).

Where changes are occurring reasonably rapidly, daily or hourly records of groundwater level behaviour are needed to capture the detail needed to investigate recharge from various sources including rainfall deep drainage, irrigation deep drainage, river recharge or flood events. Daily water level data allows a much wider range of analysis tools and interpretations to be applied, as illustrated by Dutta and Silburn (2005) and Silburn et al. (2006).

While simple water level difference maps are good for locating areas of excessive extraction, a more comprehensive analysis is required in order to separate anthropogenic and climatic responses. Flood recharge events contribute significantly to average aquifer recharge estimates when the average recharge is determined over multiple decades. Thus if groundwater usage is close to the average interdecadal recharge estimate then short term declines in the monitoring bore water levels must occur between major flood recharge events. What needs to be determined between major flood recharge events is if the rate of decline is in excess of that allowed under the expected long term average recharge to the aquifers. To determine if the rate of decline is excessive a protocol needs to be established to present aquifer stress in relation to the viable use along the lines of the methodology proposed by Punthakey (2005). Part of the methodology proposed by Punthakey uses Bollinger Bands, which are commonly used in stock markets to examine share price stress, but as Punthakey demonstrates Bollinger Bands can also be used to examine aquifer stress.

5.2 Metering of Groundwater Use
In the Condamine Groundwater Management Area (CGMA) all groundwater used for irrigation and other major uses has been metered since 1978/79, and in other declared areas more recently. This provides a good base of information for managing the aquifer and for calibrating groundwater models. Although, there are still limitations with the way the metered volumes are reported with respect to how groundwater modelling is normally calibrated. This is discussed in more detail below.

5.3 Development and Management of the Groundwater Resources
A short history of development and management of the CGMA (supplied by Greg Murphy, NRW, personal communication) follows.

- Groundwater development and use for irrigation purposes commenced in a limited way in the 1940s; by 1960 there were about 800 hectares irrigated from groundwater; over the ensuing decade to 1970 the area irrigated increased to 20 000 hectares.

- In March 1960, part of the area and, in September 1966, the balance of the area was declared under the then Water Act as a district of sub artesian supply requiring existing and proposed drilling of irrigation bores and the associated taking of water to be licensed.

- By 1969, the aquifer system in the central part of the area had become depleted, in particular the uppermost unconfined system.
• Initial groundwater allocations were granted on the basis of demonstrated development/use including development in progress; much of the development was in place prior to licensing being necessary.

• From April 1969 a maximum annual allocation of 2.5 ML/ha of property area over alluvium was imposed; also that maximum property combined rate of take was not to exceed 12.6 L/s per 40 ha of property area overlying alluvium.

• In April 1970, a Condamine Restricted Licence Area was established and an embargo was placed on the issue of new irrigation licences.

• From that time, maximum property groundwater allocations were determined at the smaller of 1.5 ML/ha of property alluvial area or 2000 hours pumping volume per annum from all bores on the property.

• Following the 1970 allocation arrangements, some of the larger established users negotiated allocations up to 3 ML/ha of property area based on demonstrated development and use.

• During 1978/79, water meters were installed throughout a Condamine Groundwater Management Area (CGMA) which was a larger area than the Condamine Restricted Licence Area.

• Groundwater charges were introduced in 1980 and excess water use charges were implemented in 1982.

• Metering and excess water use charges reduced use from an estimated 75 000 ML/a to 42 500 ML/a.

• Management Guidelines were implemented from 1980.

• Various initiatives involving the exchange of groundwater allocation for surface water entitlement were introduced in the early 1980's to reduce groundwater use.

• Access to allocations under announced arrangements were reduced from 100% to 80 % in Sub Area 3 of the CGMA, the area of highest development and use density, in 1995 and further reduced to 70% in 1996.

• Water Sharing Rules were implemented in 2002.

• Administrative Holds on new or increased entitlements have applied to the Condamine Alluvium outside of the CGMA, including the Tributary alluvia since 1996.

• Extensive investigations into enhancing recharge through artificial means have been undertaken (Lane, 1974, 1977, 1979).

While licensees have a set allocation, the real allocation is an ‘announced allocation’, sometimes of a lesser amount, which is adjusted according to climatic trends and the monitored behaviour of the groundwater.
5.4 Uncertainties in Closing the Catchment Water Balance

There are aspects of the data collection that will always result in some uncertainty in determining the available yield and the dynamics of water movement through the aquifers. These include:

- licensing of subartesian domestic bores has never been required,
- metering of stock and domestic bores has not been required,
- water level data records are only quarterly, making it difficult to model pulse events, and
- extractions at irrigation bores have not been reported on a monthly basis, yet most groundwater models are done using monthly time steps.

For these reasons all groundwater modelling will contain some level of uncertainty in the available yield estimates and quantifying recharge locations and rates.

5.5 Suggested Improvements in the Groundwater Monitoring Data

There are a number of ways in which groundwater monitoring can be improved for future assessments in the Condamine Catchment. These include that:

- the groundwater monitoring network should be reviewed with respect to fitness for purpose. It is likely that some new monitoring bores in key gaps would be helpful, especially as some shallow bores have gone dry with progressive depletion;
- data loggers be installed in a network of bores to give spatial and suitable depth coverage of the alluvial aquifer where more rapid responses are anticipated. For analysis such as recharge estimation, this should include loggers in bore lines across the river, with water level also recorded in the river, to detect any interactions (geophysics would enhance the selection of such sites);
- metering of extractions at irrigation bores should be reported on a monthly basis to aid calibration of groundwater modelling; and
- metering should be extended to the entire Condamine Catchment (this is a higher priority).

6 Condamine Groundwater Models

The Condamine Catchment is subdivided into 19 groundwater management areas (Figure 9). These zones are based on a combination of hydrogeology (geology, yield and chemistry) and extent of usage. Only the estimates and models for the Condamine Groundwater Management Area (CGMA) are discussed in this report. Six government estimates and one consulting firm estimate of the volume of groundwater that can be extracted in a viable manner each year for the CGMA were located as part of this review. The estimates are summarised in Table 1. The exact area covered by each estimate is slightly different, but the bulk of the area of concern is similar. The area modelled in more recent models is shown in Figure 10. The time period considered also varied and therefore the yield estimates will differ somewhat. The hydrogeological and yield assessments of Lane (1978) and Huxley (1982) were classic studies for their time. These studies were underpinned with some of the most intensive and extensive data collected for any alluvial aquifer system in the State (Gregory Murphy, NRW, personal communication).
Figure 9. Condamine Catchment groundwater management units (courtesy QLD NRW).
Estimates for the available yield range from as low as 13,000 ML/year to a high of 34,000 ML/year. Metered usage in the CGMA from 1980 to 2006 ranged from 23,500 to 74,000 ML/year, averaging 44,600 ML/year (David Free, NRW, personal communication). Thus the average usage exceeds all estimates of the available yield of the aquifers.

The lump parameters approaches by Lane (1978), Huxley (1982c) and Hillier (1989) have been superseded in recent decades by finite difference (MODFLOW) and finite element (FEFLOW) methods, because if constructed correctly the MODFLOW and FEFLOW models can better capture the spatial and temporal behaviour of aquifers. MODFLOW and FEFLOW models are now commonly used around the world to determine defensible well protection zones, yield estimates, flow paths and to make predictions on future aquifer response to various activities. Groundwater models can help with quantifying how well the spatial groundwater dynamics within an aquifer are understood. Where the modelling is correctly calibrated the groundwater models can inform decision makers on the impact of various water allocations scenarios.

There have been three MODFLOW models built for the CGMA: Young (1990), Richards (1992) and Bengtson (1996). The MODFLOW model by Young (1990) was produced as part of a project which was to review the hydrology of the CGMA and identify potential for and constraints on further development. The original intention was to produce a groundwater flow model and integrate it with the surface water allocation model. This integration did not occur (Linda Foster, personnel communication). Richards (1992) recalibrated Young’s model with updated water level and metered groundwater usage data. The yield calculations from these models were not used to set entitlement in the system (Linda Foster, personnel communication). The modelling undertaken by Bengtson (1996) had the stated goals of “testing the accuracy of the pervious calibrations”, to “re-calibrate the model if considered warranted”, and to “estimate the sustainable yield of the CGMA”. This was part of a training exercise and has never been considered in managing the CGMA (Linda Foster, NRW, personal communication).

All three MODFLOW models have the same core structure. They have a coarse cell size with too few cells trying to represent too large an area and they all treat the aquifer as a single layer. A review of the Bengtson (1996) MODFLOW model against the Murray-Darling Basin (MDB) groundwater flow modelling guidelines (Middlemis et al., 2000) is given in Appendix 1. This model was reviewed because it was the last in the series of MODFLOW models for the CGMA. Because of the simplifications adopted in the existing MODFLOW models none would score well if compared to the MDB groundwater flow guideline checklist.
Figure 10. Extent of the groundwater model for the Condamine Groundwater Management Area used in more recent NRW groundwater models.
None of the MODFLOW models provide a framework to develop a better understanding of the spatial groundwater dynamics occurring within the CGMA, and would be of limited value in guiding decision makers. A soundly constructed MODFLOW model can provide a useful tool for scenario evaluation. A new coupled surface and groundwater model would be needed for the Condamine Alliance area if groundwater flow modelling is to improve understanding the physical movement of water through the aquifers or to guide decision makers on water usage and impacts.

This CGMA aquifer system is large and complex. The basic complexities of a large and relatively deep, multiple and differential head system have been progressively compounded as a result of significant amendments to flow field geometry, aquifer hydrualics, storage trend and dynamics and the relationship between in-system and hydraulically connected peripheral water balance components (Greg Murphy, QLD NRW, personal communication). It is also now interacting more than in the past with areas outside the declared CGMA due to drawdown and flow from outside, and increased pumping in those outer areas.

The science of groundwater modelling, the tools available for handling large data sets and the computational power available have changed rapidly in the last decade. Improvements in the MODFLOW modelling can be made by:

- using more and smaller cells in the model,
- extending the model to include hydraulically connected areas,
- considering the various layered aquifers where possible,
- ensuring that the model is calibrated over a long enough time period in relation to the cumulative rainfall departure graphs in Section 14,
- considering deep drainage under irrigated crops in recharge estimation explicitly (e.g. using the SPLASH package of QLD NRW), whereas in the past it was considered implicitly but could not be seen separately,
- assessing the possible volume of deep drainage from ring tanks (farm dams) and if necessary incorporating into groundwater models,
- reinvestigating the contribution to groundwater recharge from the rivers and linking the MODFLOW model to a modern river flow package; the low density of the river flow gauging stations is somewhat problematic (e.g. SKM (1998) had problems calibrating their Sacramento surface water model because of this), and
- adding new rainfall gauging stations, as the density of the rainfall gauging stations is low which results in significant uncertainty in dispersed recharge to the aquifer.

There is considerable uncertainty in modelling such a large and complex aquifer system. The estimated available yields can only be considered approximate figures, and ideally should be presented as a probability distribution rather than a single figure. It is suggested that future adjustments to groundwater usage should be informed by calculating a new available yield estimate using current best practice catchment water balance modelling. Given the economic importance of the irrigation industry to the local economy and the fact that Dalby, Pittsworth and Millmerran obtain urban supplies from this alluvial aquifer it is critical that improved available yield modelling approaches be adopted. However, it is apparent that use of groundwater in the CGMA greatly exceeds the available yield, as indicated by the usage and yield estimates and by the continual decline in water levels in and around the area. Thus for long term viable use of the groundwater it is clear that there is a need for a reduction in current groundwater usage. Resource management decisions should not be delayed while further investigations and modelling are occurring.
7 Major Ion Chemistry of the Rivers and Alluvial Aquifers

Analysis of the major ion chemistry is important for understanding the migration of the water through the catchments. The water starts with the chemistry of rainwater and as the water migrates through the sediments and rock, the chemistry of the water will reflect the chemical interactions that occur, leaving the water with a diagnostic major ion composition. The major ions in natural water are Na\(^+\), K\(^+\), Ca\(^{2+}\), Mg\(^{2+}\), Cl\(^-\), CO\(_3\(^2-\), HCO\(_3\(^-\)\), and SO\(_4\(^2-\). By graphing the ions in a triaxial graph called a Piper diagram the hydrochemical facies of the water (or water types) can be determined. Further details on this style of analysis are discussed in Fetter (1988).

In 1979 major ion water chemistry measurements were made at 340 bores and stream sites in the Condamine alluvia and major tributaries. An extensive analysis of this data set was undertaken by Huxley (1982a,b). A Piper diagram of the measurements is shown in Figure 11. It can be seen that each tributary has a distinct signature and that extensive mixing occurs as the groundwater migrates down gradient. Huxley (1982a) stated that “the alluvial groundwater changes from a low salinity magnesium bicarbonate type water in the upstream areas associated with the Main Range Volcanics to relative high salinity sodium chloride type water in the downstream areas according to the following pattern:

\[
\text{Mg(Ca)-HCO}_3^- > \text{MgNa-HCO}_3^-\text{Cl} > \text{NaMg-ClHCO}_3^- > \text{NaCl}.
\]

The groundwater chemical evolution and the associated geology are shown in Figure 4.

There have been measurements of major ion groundwater chemistry in 1984, 1988, 1991, 2001, 2002, 2003, 2004, and 2005, but these data have not been comprehensively analysed since Huxley (1982a). The work by Huxley (1982a) and McNeil and Horn (1997) needs to be updated for the Condamine Catchment in a similar manner to the way the work by Gates (1980) in the Mooki has been updated by Lavitt (1999) and the work by Williams (1986) in the Lower Namoi was updated by McLean (2003).

8 Age of the Groundwater

Isotopes are used to determine the age of the water, and can also help with determining how the various sources of water in the aquifer are mixing. No isotope studies were found for the alluvial aquifers of the Condamine River. There has been some isotope work undertaken in the Hodgson Creek catchment (Cresswell, et al. 2006) and this style of investigation needs to be extended throughout the Condamine Catchment.

It is recommended that, along with any major water chemistry surveys undertaken in the future, isotope studies also be undertaken.
Figure 11. Piper diagram showing the distribution of the major ion groundwater chemistry for the Condamine River and tributaries (Huxley, 1982a).
9 Groundwater Quality

9.1 Salinity of the Alluvial and Bedrock Aquifers

A large number of water quality samples have been collected from private and QLD NRW monitoring bores in the Condamine Catchment and are stored in the QLD NRW groundwater database. A proportion of the monitoring bores is sampled each year, so that most bores are sampled every few years. The expectation is that any change in chemistry will be reasonably slow. For example, in 2005, 118 bores out of the 477 NRW bores were sampled. Some shallow bores have gone dry, particularly in the main pumped section of the Condamine alluvia, and thus can not be sampled.

From Figure 5 it can be seen that groundwater salinity above crop tolerance levels occurs near Chinchilla, in the central plains north of Pittsworth and west of Oakey, in the eastern hills north of Toowoomba, and in the western margins north of Millmerran. It is important to note that, in all areas in this 2D representation of the data, the fresh water zones used for irrigation are adjacent to saline water. No studies have been undertaken to examine the rate of movement of the saline water in areas where the aquifer is being heavily used.

At any one location the number of measurements is now becoming large enough that statistical analysis of trends can be examined. The limited number of samples per bore makes analysing for trends difficult, but nonetheless worth attempting given the large number of samples spatially.

In 1997 McNeil and Horn undertook a study of the trends in groundwater water quality and found that between Dalby and Chinchilla the salinity trends were variable, but between Dalby south to the convergence of the north anabranch and main channel of the Condamine River the groundwater salinity is probably rising. A broad scale assessment of trends in salinity is being undertaken by Pearce and Reading (QLD NRW, personal communication). However, a comprehensive statistical and 3D analysis of the existing data, along with a new systematic water quality survey is needed in order to understand how the waters within various zones of the aquifer are mixing.

9.2 Pesticides

In the limited number of bores that were sampled in the Millmerran area there were no pesticides detected (Wilson and Adams, 2004). However, pesticide data for the Condamine River show that atrazine, endosulfan, prometryn and metolachlor have at times been detected in the water. Thus, where the Condamine is a losing stream it is likely that some level of pesticide contamination is occurring in the shallow alluvial aquifer, but the extent is unknown. Further investigation in areas of groundwater recharge should be undertaken to determine if there are any ongoing concerns.

A study of the potential for groundwater contamination (“groundwater vulnerability”) was conducted in the Condamine, but is not reviewed here (Refer Stenson M.P. and Hansen A 1998 – 2002; http://www.connectedwater.gov.au/resources/Hydrogeology_Data.html).
10 Groundwater Impacts on River Water Quality

Salinity is of concern with respect to crop health, aquatic ecosystem health, infrastructure and catchment targets. There are three pathways for groundwater to influence surface water quality:

1) rising shallow groundwater levels,

2) extracted salts with the pumped groundwater slowly concentrating in the irrigated fields, channels and dams, and

3) groundwater discharging to the rivers and streams.

Pathways 1 and 3 have been reviewed by Power et al. (2005). For pathway 2 there has been limited research undertaken in the past. Power et al. (2005) report that the median electrical conductivity of the Condamine River at Chinchilla is 452 µS/cm, which is below the level of concern for irrigated crop use. There is no baseflow (groundwater discharge) in the Condamine River through the central Condamine alluvia and the river is a large source of recharge to groundwater. The groundwater surface is below the bed of the river and groundwater flow is away from the river (Lane 1979). Therefore it is unlikely that groundwater will affect the river in the central Condamine alluvia. Thus the main salinity issues in the Condamine alluvia area are (a) increasing soil salinity or sodicity (Section 11) due to application of groundwater for irrigation, and (b) possible increases in groundwater salinity discussed in Section 9.1.

Walker et al. (1998) examined historical data for larger catchments in the Murray-Darling Basin and concluded that there was no trend with respect to salinity for the Condamine River, consistent with the results of McNeil and Clarke (2005). McNeil and Clarke (2005) reviewed stream water quality trends in the Condamine Catchment. Water quality data were corrected for flow and subjected to rigorous statistical tests. They concluded that:

- electrical conductivity (EC) trends could be statistically analysed at 11 sites for 20 years, 14 sites for 10 years, and 14 sites for 5 years;

- over the last 20 years, EC has tended to fall or remain stable in the central region between Toowoomba and Dalby, particularly in the Oakey Creek catchment. A small area of the eastern headwaters south of Warwick showed a tendency for EC to rise. Elsewhere, EC was stable in the long term;

- based upon EC, total suspended solids (TSS), total nitrogen (TN) and total phosphate (TP), the general condition of water quality in the upper Condamine Catchment has not changed greatly over the past 10 years. This is against a background of high variability and limited sampling frequency; and

- Stream flow has declined at many sites since the 1970s or 1980s.

Because there is no end of valley trend in salinity does not mean that there are not local areas of concern. In many regions of the Condamine Catchment the shallow depth to groundwater (less than 5 metres) indicates the potential risk for dryland salinity outbreaks. There are regions where the shallow water table is rising, and in these areas there is potential for dryland salinity outbreaks. This is addressed in Biggs and Power (2002) and Power et al. (2005), and in detail in a salinity risk assessment of the Condamine Catchment by Biggs et al. (2006).
11 Groundwater Sodium Adsorption Ratio

One indicator of the water quality and its impact on soil and crop health is the Sodium Adsorption Ratio (SAR). This ratio examines the amount of excess sodium in relation to the combined available calcium and magnesium. The SAR value is defined as:

\[
SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}
\]

where ion concentrations are typically expressed in milliequivalents per litre (Hem, 1989). Where SAR levels are above 15, there is an excess of sodium which will be adsorbed by soil particles. This is detrimental to soil structure and makes it difficult for plants to adsorb water (Munshower, 1994). Water with high SAR can cause soil dispersion and structural problems, but this depends on the soil salinity (NRW, 2006). Further details on the SAR are presented in Fetter (1988).

Islam (2006) mapped the SAR of groundwater at 100 sites throughout the Condamine Catchment (Figure 12). The map indicates that in general the SAR value is good throughout the region. There are several isolated points of concern in the Dalby district and a major area of concern near Chinchilla in the north of the map.

![Index map of SAR distribution](image.png)

Figure 12. Groundwater SAR levels in the Condamine Catchment (Islam, 2006).
12 River Salinity Measurements: An overlooked error in determining salt loads

One observation that has been made by the authors is that no corrections are being made for the clay content of the river water when measuring the electrical conductivity of the water then converting it to total dissolved salts. Without corrections for the clay content, the total salt levels are possibly being overestimated.

Throughout the irrigation districts of NSW and QLD many of the soils contain significant quantities of clay with very high cation exchange capacities. The higher the cation exchange capacity the larger the number of charge carriers and the better the clay will conduct electricity. When the clays are dispersed in the water they act just like dissolved salt in that they help conduct electrical currents. Corrections for clay content on the electrical properties of sediments and rocks is frequently done in the petroleum industry and the electrical properties of clays have also been extensively studied by chemists studying colloidal science (Waxman and Smits, 1968; Shainberg et al. 1980, Kelly, 1994; Emerson and Yang, 1997). Emerson and Yang (1997) present data that show that the Bentonite clays of NSW are highly conductive.

13 Surface and Aquifer Water Interactions

13.1 Deep Drainage and the Unsaturated Zone

The only high resolution data for deep drainage under irrigation in the Condamine Catchment are being collected by Des McGarry and colleagues (QLD NRW) at three experimental farm sites located near Macalister, Dalby and Pampas. Their research is investigating deep drainage under irrigated cotton. From the preliminary deep drainage results that have been published (McGarry et al., 2005) it can be seen that much work is needed to improve catchment water balance modelling for recharge estimation. The barrel lysimeter data indicate that approximately 10% of the irrigation water goes to deep drainage throughout the growing season. At the moment irrigation deep drainage is not assigned as an input in aquifer water balance models of the Condamine Catchment. A quick calculation for the Condamine Catchment shows that this is a significant gap in our understanding of the water accounting. Assuming 30,000 hectares of irrigated cotton (The Australian Cottongrower, 2006) and if 4.3 ML/hectare of irrigation water is used (Goyne et al., 2000) and 10% of the irrigation water goes to deep drainage throughout the irrigation season then 13,000 ML of water migrates downwards towards the shallow aquifers. To put this volume of water into perspective, this is the same order of magnitude as the reported total recharge estimate for Condamine alluvial aquifers.

Lane (1979) took the view that deep drainage would not occur on the heavy clay soils of the Condamine alluvia, even where water was ponded, and had several pieces of supporting evidence. However, since then there has been mounting evidence that deep drainage occurs on heavy clays under dryland cropping (Tolmie et al., 2003, in prep.) and under irrigation (Silburn and Montgomery, 2004; McGarry et al., 2005). If drainage occurs under dryland cropping it is logical that even more drainage occurs with irrigation. However, the deep drainage has to fill a historic soil water deficit to many meters depth before it will reach the groundwater surface and become recharge. Lane (1979) confirmed that the unsaturated zone below the root zone is reasonably dry. Sampling of soil moisture under brigalow by Tolmie et al. (in prep.) found a large soil moisture deficit with an available water storage capacity of approximately 640 mm between 1.2 and 7 m. Under a neighbouring dryland cropped site, 313 mm more water was stored to 7.2 m depth (below 1.2 m). This difference in water content is assumed to be new water stored since clearing 38 years ago. Jolly et al. (1989) found similar profiles of new (post-clearing) water where Mallee vegetation was cleared in South Australia.
Before this recharge component is added to any groundwater models more work is needed to determine how much of this water recharges the shallow water table and then the productive aquifers, and the time lag between irrigation and potential aquifer recharge. Also, it may not be appropriate to scale between point measurements of deep drainage at a limited number of sites to regional scales. More work is needed to clarify scaling of data. Clearly, there are major gaps in our understanding of water movement and water accounting.

The barrel lysimeter work needs to be combined with monitoring of the shallow water table using data loggers at each location, and with measurements of the moisture status and storage capacity of the unsaturated zone. This work needs to be linked closely with catchment water balance modelling.

### 13.2 River – Groundwater Interaction

In general, upland catchments in the west, south and eastern ranges in the Condamine Catchment are ‘gaining’ streams on average. That is, they have baseflow in times between flood flow events, supplied by groundwater discharge (e.g. Silburn et al., 2006). In contrast, the main Condamine River in the alluvia has little baseflow (Lane, 1979) and is losing water to groundwater. The elevations of the water surface in the main aquifers are well below the bed of the stream and the water levels indicate groundwater flow away from the river. This form of recharge is confirmed by the groundwater salinities – similar to river water near the river and more saline further from the river (Lane, 1979).

Modelling of surface and groundwater interactions has been undertaken in small catchments like Hodgson Creek (Silburn and Owens, 2005) using 2CSalt modelling. This style of modelling is of value in upland catchments, but is not designed for use in the central Condamine River alluvia. Coupled river and aquifer modelling using MODHMS or similar packages is needed to capture the movement of salts within the aquifers used extensively by the irrigation industry.

In order to improve the modelling of movement and interaction of surface and ground waters, high resolution (hourly or daily) data are needed on the rate of transfer of surface water to the aquifer from irrigation deep drainage, diffuse rainfall recharge, losing stream reaches, and floods. This high resolution information is needed to improve both the GIS based deep drainage modelling (Yee Yet and Silburn, 2003) and for MODHMS modelling.

Options for artificial or induced recharge to groundwater were extensively investigated by Lane (1974, 1977, 1979). However, the only sources of water are the Condamine River and overland flows, which are fully allocated.
14 Three Dimensional Visualisation and Data Management

In the process of obtaining information for the preparation of this report it has become apparent that data management relating to the groundwater resources is not in keeping with modern practices adopted by the mining and petroleum industries. Ideally the groundwater data should be publicly available, as is the case in the USA (http://waterdata.usgs.gov/nwis/gw).

Also, the data need to be analysed in a 3D environment to highlight gaps in our data collection and to show the full complexity of the alluvial environments. The authors believe that it would make a valuable communication tool that could help with improving the management of the aquifers. We live in a 3D world so it is best that we explore it that way. When we try to represent a complex environment in 2D simplification and oversights occur. This diminishes our capacity to deliver best management practices. By representing 3D geological information in 2D we are not accurately representing our knowledge of the aquifers. Often monitoring well hydrographs are processed in isolation and information from various aquifer depths covering tens to hundreds of metres are collapsed into 2D maps. This results in a simplified interpretation of the aquifers. All major petroleum and mining companies invest in 3D data interpretation and visualisation, because it reduces errors, provides a valuable communication tool and maximises the financial returns from the resource. An example of a 3D geological model of an aquifer from the USA is shown in Figure 13.

![Figure 13](image_url)

**Figure 13.** A 3D geological model of the Edwards Aquifer, Texas, U.S.A., showing bore locations (yellow lines), formation top picks (dots), geological formations (coloured layers) and faults (red lines). Model courtesy Dynamic Graphics Inc, USA.
15 Future Issues

15.1 The Implications of Past Climatic Rainfall Trends

Rainfall in the Condamine Catchment has been collected continuously since the 1880s. It is clear from the records that the latter half of last century was wetter than average. The data also indicate that dry runs of below average rainfall can last from 20 to 50 years. The wet and dry runs become evident by graphing the data in a Cumulative Rainfall Departure graph (CRD). CRD graphs are also called residual mass graphs. To generate a CRD graph:

1) Subtract the average rainfall from the yearly total to give a residual (the average is determined from complete rainfall record),

2) Keep a running tally of the sum of the residuals.

The CRD graphs for Warwick, Toowoomba, Pittsworth, and Dalby are shown in Figures 14 and 15. At all locations a dry run can be seen in the earlier quarter of the 1900s followed by a wet run in the later half of the 1900s. This presentation of the data clearly shows that the modern cotton industry, which expanded from the 1960s through 1980s, was established in a wet run. The recent drought conditions are indicated by the downward run on the right hand side of each graph. If the irrigation industry were to be faced with dry runs of the duration experienced in the early part of last century there would be significant additional pressure on water availability and financial implications for all irrigation districts.

Most of our living memory of climatic conditions has been derived during a wet run and this has biased our personal experience of “what is normal”. But it is clear in all graphs that for the majority of the 1960s until the 1990s it was wetter than average compared to the last 120 years of rainfall records. So the period over which the current catchment water balance models (both surface and ground waters) have been calibrated and available yields determined has given false expectations of how much water is available on average. It should be possible to link the trends displayed in cumulative rainfall departure graphs to other climatic variables such as the Southern Oscillation Index and other Pacific and Indian ocean temperature and pressure indices, so that a long range forecasting tool could be established. These trends could then be linked to aquifer response. This would allow irrigators to better manage future water stress risks.

In areas of no pumping, or balanced pumping, there is a strong link between the cumulative rainfall departure and monitoring bore water levels located in the shallow aquifers. In areas of excess pumping, or excessive deep drainage, there is a poor correlation.

In the examples from Warwick and Clifton districts (Figures 16 and 17) the monitoring bore water level trends reflect those of the cumulative rainfall departure, showing the close link between rainfall and aquifer recharge. Near Pittsworth the aquifer is being depleted, with no reflection of rainfall trends (Figure 18). In the Dalby and Chinchilla districts (Figures 19 and 20) the aquifers are being mined, but there are still impressions of the rainfall signature, but to a lesser extent near Chinchilla.

Systematic analysis of statistics of the hydrographs has not been undertaken throughout the Condamine Catchment, though they were considered in the salinity risk assessment of Biggs et al. (2006). Via a statistical analysis it should be possible to generate index maps of where groundwater extractions are in balance with climatic trends and where extractions are out of balance with climatic trends.
Figure 14. Cumulative rainfall departure at Toowoomba (top) and Warwick (bottom showing that the modern cotton industry (1960s onwards) was established during a predominantly wet period.
Figure 15. Cumulative rainfall departure at Dalby (top) and Pittsworth (bottom) showing that the modern cotton industry (1960s onwards) was established during a predominantly wet period.
Figure 16. Cumulative rainfall departure and bore water level fluctuations - Warwick district (Islam, 2006).

Figure 17. Cumulative rainfall departure and bore water level fluctuations - Clifton district (Islam, 2006).

Figure 18. Cumulative rainfall departure and bore water level fluctuations - Pittsworth district (Islam, 2006).
15.2 Connected Water

At both Federal and State levels there is a move to treat the river and ground water as connected and to base usage decisions on the connected water systems.

Refer:
http://www.nht.gov.au/ncc/ground-surface-water.html

A decision needs to be made by all stakeholders within the Cotton Catchment Communities CRC and the Condamine Alliance about what research needs to be supported so that all stakeholders can be part of an informed debate about management and policy direction.
15.3 Expansion of Mining and Energy Sectors

Within the Condamine Alliance area both the energy and mining sectors are expanding and both sectors are reliant on continuous supplies of good quality water. There is the proposed new Condamine power station (www.qgc.com.au) near Miles, and proposed coal seam gas sites near Braemar, Chinchilla, Dalby and Roma (QGMJ, 2006). The potential conflicts on the demand for water between the petroleum/coal sectors and the agricultural sector are discussed further in Free (2006). Throughout the Condamine Alliance area there is significant potential for the expansion of coal mining, with 30 deposits and operating mines already located within the region (www.nrw.qld.gov.au/mines/coal).

Coal production in the Surat Energy Resources Province has increased significantly in the past five years, rising from less than one million tonnes in 2001 to over eight million tonnes in 2005-06 from coal mines near Millmerran, Acland and Macalister in the Condamine Catchment. New coal mines are proposed to the west of Chinchilla at Cameby Downs and near Wandoan. Estimates indicate there are approximately 6.3 billion tonnes of raw coal (in situ) in the Surat Energy Resources Province (AEC 2007, pp8-9). The Millmerran power station and the Kogan Creek power station are the major coal users in the Condamine Catchment. Some coal is exported while other coal is used by power stations in south east Queensland.

Coal seam gas (CSG), in the Surat Energy Resources Province, has increased significantly since 1997/98, at an annual average growth of 59.1%. The total current reserves in the Surat Energy Resources Province are estimated by the Department of Mines and Energy to be 3,556 Peta-Joules (PJ). However, this is increasing every year as additional drilling is undertaken, and industry estimates suggest that total reserves will increase to between 10,000 and 15,000 PJ (AEC 2007, p9). The main coal seam gas production areas are around Dalby, Chinchilla and to the north of Roma.

Coal seam gas production is projected to grow at a rapid pace over the next five to ten years as existing CSG fields increase production to full capacity and new fields are developed. CSG production is expected to grow steadily between 2015 to 2030, from approximately 300 PJ per annum to nearly 400 PJ per annum, driven by expanding industry demand rather than power generation once CCT becomes available (AEC 2007, p24). Water is a by-product of coal seam gas production.

The production of CSG water is expected to significantly outstrip demand between 2007 and 2030. Assuming CSG water is produced at an average of 200 ML per PJ of CSG, annual production of CSG water is projected to reach 79,000 ML by 2030, more than triple the quantity of water demanded by industry. Even using an average rate of CSG water production of 100 ML per PJ of CSG, the quantity of water produced is expected to be nearly double the quantity demanded, however, water quality, reliability over time and the cost of transport infrastructure influence the suitability of CSG water for alternative uses (AEC 2007, p25). While the Queensland Government’s policy promotes beneficial use of coal seam gas water, it is mainly stored in evaporation basins because there are few alternative uses for it.

16 Concerns of Irrigators

Through phone interviews, discussions at trade shows and community meetings, irrigators were asked what they thought needs investigating. There is general awareness that groundwater in the Condamine is over allocated and that current usage levels are mining the aquifers in many areas. Because of this the dominant response was to improve the science and reduce the uncertainty in the allocation of groundwater. Following this, determine flexible management practices within a
grower’s allocation so that they could maximise the return on water use. Maximising the return has a benefit for both the grower and the community. For example, access to slightly more water at the end of a season could mean the difference between a high crop yield and return versus a loss in crop yield and quality. This additional access to water in one year would be offset by a reduction in usage in a subsequent year.

In the Condamine, there was also general support for a water quality survey to characterise current conditions. In at least one area, use of marginal quality groundwater has already led to a detrimental impact on crop yields. Investigating increased recharge was regarded by one grower as “a fantastic idea if it can be done”. There was also support for providing information on the optimisation of groundwater pumping and storage strategies. Most supported the need for an education program on hydrogeology and how groundwater modelling was used to guide determining the available yield.

One farmer in the Condamine suggested that an investigation into low flow pumps would be of value to the irrigators because in some areas the older high flow pumps could not work to capacity.

17 Concerns of Conservation Groups

The World Wildlife Fund – Australia do not have published policy positions on each catchment, but in general state (WWF-Australia, 2004) that we need to:

- develop ‘whole-of-state’ water resource planning, which accounts for all significant water use across landscapes, above and below ground, and across state borders”;
- immediately audit the status of allocation and river/aquifer health of all surface and groundwater systems; and
- Legally recognise and clearly define environmental allocations so that fundamental ecosystem functions are maintained in perpetuity.”

The Australian Conservation Foundation (ACF) has a preliminary draft Water Policy (ACF, 2006). Key items in that policy that relate to this scoping study are:

“2.1.2 River Planning and Management Principles

Planning for use of water resources from rivers must include protection of biological diversity and ecological integrity. This includes:

- Recognition of the role of riparian zones (including floodplains and wetlands) in supporting river function, providing wildlife corridors and providing an intrinsic habitat;
- An awareness of the natural processes and ecology of rivers, and the impacts human activities can have upon them (e.g. damming of rivers which affects river flows, and can lead to unnatural levels of thermal pollution and anoxic conditions);

River management must comply with the following standards as a minimum:

- A scientific assessment of what is required to restore, or secure, ecological health;
• In over-committed systems, a clear pathway for recovering sufficient water to secure river health within the life of the plan, managed in an appropriate way;

• A continuous and adaptive program of monitoring and reporting on ecological outcomes;

• Consultations around how best to meet ecological objectives;

• In surface systems, recognition of the integration between regulated surface flows, unregulated flows, and groundwater base flow discharge. In groundwater systems, recognition of the needs of groundwater dependent ecosystems; and

• A funded plan of water acquisition, where necessary.

• ACF supports Integrated Catchment Management (ICM) (also known as Total Catchment Management) as an effective planning and management model.

2.2 Groundwater

Groundwater has a critical role in supporting river and wetland functions as well as sustaining groundwater dependent ecosystems. Because of this groundwater use needs to be couched in sustainable practices being aware that:

• Recharge rates are extremely slow (i.e. groundwater use should not exceed recharge rate),

• Use of near coastal ground water has allowed infiltration of saline waters into fresh water aquifers.

• Ground water can be easily polluted.”

ACF also have a policy on the Murray-Darling Basin. Item 1.4 from that policy states:

“1.4 To provide a sound basis of knowledge for management of the Murray-Darling catchment, the ACF further advocates that a national fresh-water research body be established to, among other things:

(a) promote a coordinated approach to land use and water management practices that will allow the supply and/or quality of surface and underground waters for both natural systems and rural towns and industry to be controlled;

(b) discourage and prevent where possible, land use and water management practices that will cause either short or long term deterioration in the quantity and/or quality of surface or underground waters;

(c) ensure that all resource use and management decisions are based on a full consideration of environmental (including wildlife) effects, emphasising long term considerations for the whole catchment.”

The Total Environment Centre does not have policies published on the web with respect to groundwater or catchments of interest within the Murray-Darling Basin.
18 National Water Initiative

There is a need to match the goals of the Cotton Catchment Communities CRC and Condamine Alliance with those of the National Water Initiative (http://www.nwc.gov.au/nwi/index.cfm). The National Water Initiative has ten major goals, five of the goals have a policy and management focus, while the other five need supporting science to underpin the objective. Recommended projects that improve the science of the objectives are listed against the NWI objective in Table 2.

Table 2. A comparison of the National Water Initiative objectives with the projects recommended in this report.

<table>
<thead>
<tr>
<th>National Water Initiative Objective</th>
<th>Recommended Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>i. clear and nationally-compatible characteristics for secure water access entitlements;</td>
<td>none</td>
</tr>
<tr>
<td>ii. transparent, statutory-based water planning;</td>
<td>none</td>
</tr>
<tr>
<td>iii. statutory provision for environmental and other public benefit outcomes, and improved environmental management practices;</td>
<td>1) Measure the trends in water quality from irrigator bores. 2) Measure water quality trends in NRW bores. 3) Develop a correction for sediment load on river electrical conductivity measurements.</td>
</tr>
<tr>
<td>iv. complete the return of all currently over-allocated or overused systems to environmentally-sustainable levels of extraction;</td>
<td>1) Develop a best practice approach to water allocation modelling. 2) Compare cumulative rainfall departure data with NRW monitoring bore hydrographs. 3) Couple groundwater chemistry to the groundwater flow modelling. 4) Record deep drainage at the shallow water table. 5) Incorporate farmer rainfall data into water balance models. 6) determine the moisture status and lag time of the unsaturated zone</td>
</tr>
<tr>
<td>v. progressive removal of barriers to trade in water and meeting other requirements to facilitate the broadening and deepening of the water market, with an open trading market to be in place;</td>
<td>None</td>
</tr>
<tr>
<td>vi. clarity around the assignment of risk arising from future changes in the availability of water for the consumptive pool;</td>
<td>1) Develop a best practice approach to water allocation modelling. 2) Explore the reuse of deep drainage. 3) Areas of rising groundwater need to be investigated. 5) Examine the potential for artificial recharge.</td>
</tr>
<tr>
<td>vii. water accounting which is able to meet the information needs of different water systems in respect to planning, monitoring, trading, environmental management and on-farm management;</td>
<td>1) Develop a best practice approach to water allocation modelling. 2) Compare data from irrigator bores with nearby NRW records, 3) determine the moisture status and lag time of the unsaturated zone.</td>
</tr>
<tr>
<td>viii. policy settings which facilitate water use efficiency and innovation in urban and rural areas;</td>
<td>None</td>
</tr>
<tr>
<td>ix. addressing future adjustment issues that may impact on water users and communities; and</td>
<td>None</td>
</tr>
<tr>
<td>x. recognition of the connectivity between surface and groundwater resources and connected systems managed as a single resource.</td>
<td>1) Recharge and discharge zones along the rivers and streams need to be mapped. 2) Build a 3D model of the hydrogeology.</td>
</tr>
</tbody>
</table>
19 Conclusions

In order to make wise management decisions with respect to groundwater in the Condamine Catchment better scientific information is required, along with improved coordination and communication of existing data. There is a large quantity of historical data for the Condamine Catchment. The storage and access of these data could be updated to modern standards. Through the US Geological Survey network it is possible to access all data relating to 786,877 monitoring wells in the USA via the internet (http://waterdata.usgs.gov/nwis/gw). There is no technical reason why this cannot be done in Australia. Easy access to data would allow for better public awareness and debate on water issues. Ideally all data also need to be presented and analysed in a 3D environment.

Benchmarking of groundwater conditions is a priority. It is needed as part of development of the Water Resource Plans, it is required for good management decisions, and without reference conditions we cannot quantify improvements. 35 years of groundwater hydrograph records enable long term groundwater head trends to be analysed throughout the alluvial regions of the catchments. There is also considerable water chemistry data over the period of groundwater use. There is just enough historical data in some regions that with a new statistically valid sampling program trends in water quality could be examined.

Estimating catchment scale water balances is not an exact science. There are errors in estimating rainfall recharge, river recharge, irrigation returns to the aquifer, inflows through basement rocks, discharge via the rivers, evapotranspiration losses, surface water storage losses, and quantifying flood events. This is why catchment water balances have to be modelled and best estimates given (ideally with confidence intervals). Through improved measurement techniques, higher resolution data and advancement in numerical computer modelling techniques, the uncertainties associated with quantifying water fluxes through the catchment can be reduced and allocation decisions improved. There are several projects that could be undertaken through partners in the Cotton Catchment Communities CRC that could advance the science of catchment hydrology and improve the confidence of available yield estimates. These include:

- **Record irrigation deep drainage at the shallow water table.**

  Our understanding of how much deep drainage reaches the shallow water table is extremely limited. The initial estimates of deep drainage beneath irrigated crops indicate that we have a significant gap in our understanding of where the deep drainage water goes. The estimated volume of water is such that deep drainage may need to be accounted for as part of the catchment water balance modelling. How much irrigation deep drainage water recharges the shallow water table and then the productive aquifers is unclear, as is the time lag between irrigation and potential shallow aquifer recharge. Another important aspect of the problem is that we do not know if it is appropriate to scale up point measurements of deep drainage at a limited number of sites to regional scales.

- **Investigate the moisture status (moisture content and potential) of the unsaturated zone below the root zone, to determine how deep the drained water has penetrated under irrigated areas.**

  The deep drainage could still be filling a historic water deficit in the unsaturated zone and is therefore not yet appearing as groundwater recharge. This would help to resolve the issue discussed above.
• Incorporate farmers’ rainfall records into catchment hydrology models

The Bureau of Meteorology rainfall gauging stations are too few in number for good rainfall estimates in catchment hydrology models. Reliable farmers’ rainfall data could be included in catchment water balance models to see if it could improve the spatial information on rainfall distribution.

• Recharge and discharge zones along the rivers need to be mapped.

The mapping of recharge and discharge zones along the Condamine River is needed to constrain the processes applied in groundwater water balance modelling, and to understand the ecological impacts.

• Develop a best practice approach to catchment water balance modelling.

Monitoring bore hydrographs clearly indicate that the Condamine Groundwater Management Unit is being mined. For the portion of the irrigation industry that is dependent on groundwater supplies to be operated in a long term viable manner, new usage levels will be required.

A new groundwater model in keeping with the Murray-Darling Basin Commission groundwater flow modelling guidelines (Middlemis et al., 2000) would help guide decision makers on groundwater processes and the most probable available yield. Ideally a coupled surface and ground water modelling environment should be used.

• Determination of the climatic response of the aquifer linked to rainfall history.

If flood recharge is to be considered part of the long term available yield then the water levels recorded in the monitoring bores will decline between major flood events. A simple method for indexing areas that are in or out of balance with respect to management goals is required.

• Couple water chemistry and volumes in a single connected waters model.

The current focus on groundwater management has been on volumetric allocations. Ideally, both the volumes and quality of water need to be managed together. To achieve this higher resolution groundwater models are required.

The major issues for salinity in the central Condamine alluvia (but not necessarily elsewhere in the Condamine Catchment) are (a) the influence of heavy pumping and groundwater decline on the movement of stored salts in the shallow aquifers and in the saline areas adjacent to the fresh water intervals used for irrigation, and (b) the influence of salts and sodium applied in irrigation water. There is limited understanding of the rate of mixing, and the long term implications for crop and soil health. There is a large volume of water in the fresh water aquifers which is slowly being drawn down. So the process of mixing will be slow (years to decades). However, on a local scale the aquifer drawdown due to pumping at high volumes could cause substantial mixing of the fresh and saline waters.

In order to provide a data set to analyse the potential mixing of fresh and saline waters it is recommended that a program of measuring water quality from irrigator bores be implemented. Ideally, readings should be taken at several intervals throughout the pumping season. To complement these data, salinity readings are needed from the QLD NRW groundwater
monitoring network. This would be a larger scale project because each monitoring well would need to be pumped prior to recording a measurement.

The surface and ground water major ion and isotope chemistry of the Condamine River and tributaries needs to be systematically studied at a local scale. This would allow for an update of the hydrochemical facies and chemical evolution of the waters within the catchment. Huxley’s work gives us baseline conditions from 1979. A new hydrochemical facies analysis would allow changes over the last 28 years to be examined. Aspects of this have been undertaken by McNeil and Horn (1997), but it needs to be expanded along the lines of the work undertaken by Lavitt (1999) in the Mooki catchment, Liverpool Plains, NSW.

With respect to end of catchment management goals, there may be a need to make a correction for the clay content of the water when measuring the salinity of the river water. Many of the clays in the region have a high cation exchange capacity and these clays would add to the electrical conductivity of the water. At the moment there is no correction being made for the clay content of the water when electrical conductivity measurements are converted to salt load measurements. This could mean that the salt load of the river is being over estimated.

Expansion of coal seam gas and coal mining will have implications for groundwater use and disposal of groundwater pumped from CSG fields. A final concern in areas of excessive decline in the groundwater head is subsidence of the aquifers. This could have a significant impact on the future recharge potential of the aquifers under major flood events.
REFERENCES


Appendix 1 - Review of the Condamine Groundwater Management Area
MODFLOW Model

Modelling Overview

A model is a physical or mathematical replica of something in the real world. A mathematical model aims to capture the essence of the real world, but deliberately omits non-essential processes or details. Environmental modelling is the science and the art of simulating environmental phenomena. Often, modelling is the only way to answer “what happened” questions, by reconstructing an environmental event to establish cause and effect. Modelling certainly is the only way to answer “what if” questions, to predict the consequences of a decision or action. For water resources in particular, we could say that water modelling is a computer-based analysis of processes in the water cycle and controls imposed on water systems, for the purpose of evaluating the effects of climate or management policy/actions.

In New South Wales and Queensland, government agency river models are standardised on IQQM software and groundwater models are standardised on MODFLOW software.

IQQM (Integrated Quantity Quality Model) was developed by the (now) NSW Department of Water and Energy (DWE) to investigate the impacts of water resource management policy on stakeholders. A river is represented in the model as a series of nodes that have attached inflows, outflows and storages. The nodes are connected by links that represent water flows and routing processes. IQQM usually operates at a daily time scale, can be applied to regulated or unregulated rivers, and can simulate water salinity. In ungauged tributaries or where stream flow data are incomplete, the Sacramento rainfall-runoff model is used to infer stream flow from climate data and land use.

MODFLOW (MODular Groundwater FLOW Model) was developed in the 1980s by the United States Geological Survey as a generic simulator of groundwater flow processes in saturated aquifers (McDonald & Harbaugh, 1988). It represents an aquifer system as a three-dimensional mesh of rectangles stacked in multiple layers. It simulates rainfall recharge and evapotranspiration from a water table, but does not simulate infiltration through unsaturated soil or evaporation from vegetation or surface water bodies. A river is represented in the model as a series of cells that may or may not be connected. The “river” package requires specification of water level in the river, whereas the “stream” package routes flow along a channel. Discharge is simulated to wells, bores and drains. MODFLOW usually operates at a monthly time scale for catchment models. It does not simulate groundwater salinity but a companion product (MT3D) can simulate generic solute transport.

Condamine MODFLOW model

The current groundwater resource model in the Condamine Groundwater Management Area was developed in 1990 by the Water Assessment Group of the Queensland Water Resources Commission (Young, 1990). It was modified and re-calibrated in 1991-1992 (Richards, 1992) and again recalibrated in 1996 (Bengtson, 1996). In each case the model amendments were made by staff in the Water Assessment Group of the same department.

There has been no attempt to extend the physical limits of the model or to refine the coarseness of the model since the earliest version, although Bengtson (1996) recommended refinement of
the spatial scale. The model extent and grid dimensions are shown in Figure 10 (see the main report). The model covers an area of about 100 km north-south by 82.5 km east-west. The model has only one layer, 15 rows and 13 columns, with non-uniform cell sizes that vary from 5 km to 10 km. It has been developed using MODFLOW within a PMWIN (unstated version) framework. The transient calibration period was June 1979 to August 1989 for the two earlier versions of the model, and August 1989 to February 1994 for the latest version (Bengtson, 1996).

An appraisal of the Bengtson (1996) model according to the MDBC guidelines (Middlemis et al., 2000) is presented in Table A1. Two aims of the guideline are to provide a framework to evaluate existing models (to highlight the extent to which a model may need to be upgraded) and to guide the construction of new models.

The main problem with the model is the imposition of boundary conditions in 50 percent of the active model cells. In the northern and southern sections of the model, only one cell width separates western from eastern boundary conditions. The model has very little freedom, and is almost completely constrained. This explains why the calibration against February 1994 head contours looks almost perfect, and many of the hydrograph matches appear very good. In cells away from the boundary conditions, the model does a poor job of replicating hydrographic fluctuations.

The over-reliance on imposed boundary conditions has resulted from a very coarse discretisation and an inadequate model extent. This can be remedied easily in future models.

While PEST has been used to infer storage, transmissive and recharge parameters, and that is to be encouraged, the resulting parameter distributions are not sensible. The resulting patterns are essentially random. Specific yield values in adjacent cells vary from 0.1% to 20%. Hydraulic conductivities in adjacent cells vary from 0.1 to 74 m/day, and from 1 to 200 m/day. Rainfall infiltration is inferred to be zero directly above an obvious groundwater mound.

Reporting is poor. No input datasets are given; there is no mention of metered use volumes; there is no rainfall analysis; there is no streamflow analysis; there is no attempt to analyse cause and effect on field hydrographs to inform conceptualisation. The reported water budget is incomplete in that only the inflows to the water balance are noted. Similar comments also apply to the reporting by Richards (1992).

Given that the Condamine alluvial sequences are known to be complex in structure, have both semi and unconfined portions and are undergoing changes in flow dynamics due to the past level of extraction then the existing MODFLOW models of the region do not help with capturing the dynamic behaviour of the groundwater systems, they do not extensively help with understanding the recharge and discharge processes, and if used for giving a guiding figure on the available yield of the aquifers they would have a large degree of uncertainty.

Any future MODFLOW models developed for the region should be guided by the procedures outlined in the MDBC groundwater modelling guidelines (Middlemis et al., 2000). In order to give insights into the spatial groundwater dynamics the model should try to honour more closely the complexity of the hydrogeology of the alluvial aquifers.
Table A1. Model Appraisal: Condamine Model 1996

<table>
<thead>
<tr>
<th>Q.</th>
<th>QUESTION</th>
<th>Not Applicable or Unknown</th>
<th>Score 0</th>
<th>Score 1</th>
<th>Score 3</th>
<th>Score 5</th>
<th>Score Max. Score (0, 3, 5)</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>THE REPORT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>Is there a clear statement of project objectives in the modelling report?</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td>Post-audit, recalibration, and sustainable yield</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>Is the level of model complexity clear or acknowledged?</td>
<td>Missing</td>
<td>No</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>Is a water or mass balance reported?</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td>Inflows are quantified, outflows are not. SY = 34 GL/year.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>Has the modelling study satisfied project objectives?</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td>Objectives are addressed (but of little use)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>Are the model results of any practical use?</td>
<td>No</td>
<td>Maybe</td>
<td>Yes</td>
<td>Model is controlled by boundary conditions.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>DATA ANALYSIS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>Has hydrogeology data been collected and analysed?</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td>No pumping tests.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2</td>
<td>Are groundwater contours or flow directions presented?</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td>Only Feb 1994</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.3</td>
<td>Have all potential recharge data been collected and analysed? (rainfall, streamflow, irrigation, floods, etc.)</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td>Streamflow &amp; irrigation &amp; floods not reported.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.4</td>
<td>Have all potential discharge data been collected and analysed? (abstraction, evapotranspiration, drainage, springflow, etc.)</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td>Metered use included but not reported</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>Have the recharge and discharge datasets been analysed for their groundwater response?</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td>No cause &amp; effect analysis of hydrographs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.6</td>
<td>Are groundwater hydrographs used for calibration?</td>
<td>No</td>
<td>Maybe</td>
<td>Yes</td>
<td>Large number.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.7</td>
<td>Have consistent data units and standard geometrical datums been used?</td>
<td>No</td>
<td></td>
<td>Yes</td>
<td>Rainfall infiltration is expressed as mm, but ambiguous as to time period</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>CONCEPTUALISATION</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>Is the conceptual model consistent with project objectives and the required model complexity?</td>
<td>Unknown</td>
<td>No</td>
<td>Maybe</td>
<td>Yes</td>
<td>Multi-level piezometers should be inspected to justify single layer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.2</td>
<td>Is there a clear description of the conceptual model?</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.3</td>
<td>Is there a graphical representation of the modeller’s conceptualisation?</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.4</td>
<td>Is the conceptual model unnecessarily simple or unnecessarily complex?</td>
<td>Yes</td>
<td>No</td>
<td></td>
<td>Unnecessarily simple and too coarse.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.0</td>
<td>MODEL DESIGN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.1</td>
<td>Is the spatial extent of the model appropriate?</td>
<td>No</td>
<td>Maybe</td>
<td>Yes</td>
<td>Too much reliance on estimated boundary inflows. Model extent should be widened.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>Are the applied boundary conditions plausible and unrestricted?</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td>Model is completely controlled by imposed boundary conditions.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.3</td>
<td>Is the software appropriate for the objectives of the study?</td>
<td>No</td>
<td>Maybe</td>
<td>Yes</td>
<td>PMWIN &amp; MODFLOW</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table A1 continued - Model Appraisal: Condamine Model 1996

<table>
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<tr>
<th>Q.</th>
<th>QUESTION</th>
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<th>Score 1</th>
<th>Score 3</th>
<th>Score 5</th>
<th>Score Max. Score (0, 3, 5)</th>
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<tbody>
<tr>
<td>5.0</td>
<td>CALIBRATION</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.1</td>
<td>Is there sufficient evidence provided for model calibration?</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td></td>
<td>Contour map and many hydrographs</td>
<td></td>
</tr>
<tr>
<td>5.2</td>
<td>Is the model sufficiently calibrated against spatial observations?</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td></td>
<td>Simulated WL contours appear excellent, but this is due to boundary conditions</td>
<td></td>
</tr>
<tr>
<td>5.3</td>
<td>Is the model sufficiently calibrated against temporal observations?</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td></td>
<td>Some very good matches, but due to boundary conditions. Model does not capture hydrograph dynamics.</td>
<td></td>
</tr>
<tr>
<td>5.4</td>
<td>Are calibrated parameter distributions and ranges plausible?</td>
<td>Missing</td>
<td>No</td>
<td>Maybe</td>
<td>Yes</td>
<td></td>
<td>Wide variation in calibrated properties; unreasonable spatial patterns; illogical rain recharge distribution</td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td>Does the calibration statistic satisfy agreed performance criteria?</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td></td>
<td>Use of PEST guarantees optimal overall statistics (but not reported)</td>
<td></td>
</tr>
<tr>
<td>5.6</td>
<td>Are there good reasons for not meeting agreed performance criteria?</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.0</td>
<td>VERIFICATION</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.1</td>
<td>Is there sufficient evidence provided for model verification?</td>
<td>N/A</td>
<td>Unknown</td>
<td>No</td>
<td>Maybe</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.2</td>
<td>Does the reserved dataset include stresses consistent with the prediction scenarios?</td>
<td>N/A</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.3</td>
<td>Are there good reasons for an unsatisfactory verification?</td>
<td>N/A</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.0</td>
<td>PREDICTION</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.1</td>
<td>Have multiple scenarios been run for climate variability?</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td></td>
<td>Not an objective</td>
<td></td>
</tr>
<tr>
<td>7.2</td>
<td>Have multiple scenarios been run for operational /management alternatives?</td>
<td>N/A</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.3</td>
<td>Is the time horizon for prediction comparable with the length of the calibration / verification period?</td>
<td>N/A</td>
<td>Missing</td>
<td>No</td>
<td>Maybe</td>
<td>Yes</td>
<td></td>
<td></td>
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<tr>
<td>7.4</td>
<td>Are the model predictions plausible?</td>
<td>N/A</td>
<td>No</td>
<td>Maybe</td>
<td>Yes</td>
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<tr>
<td>8.0</td>
<td>SENSITIVITY ANALYSIS</td>
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</tr>
<tr>
<td>8.1</td>
<td>Is the sensitivity analysis sufficiently intensive for key parameters?</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
<td></td>
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<tr>
<td>8.2</td>
<td>Are sensitivity results used to qualify the reliability of model calibration?</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
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<tr>
<td>8.3</td>
<td>Are sensitivity results used to qualify the accuracy of model prediction?</td>
<td>Missing</td>
<td>Deficient</td>
<td>Adequate</td>
<td>Very Good</td>
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<tr>
<td>9.0</td>
<td>UNCERTAINTY ANALYSIS</td>
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<tr>
<td>9.1</td>
<td>If required by the project brief, is uncertainty quantified in any way?</td>
<td>Missing</td>
<td>No</td>
<td>Maybe</td>
<td>Yes</td>
<td></td>
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<tr>
<td>TOTAL SCORE</td>
<td>PERFORMANCE:</td>
<td>%</td>
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