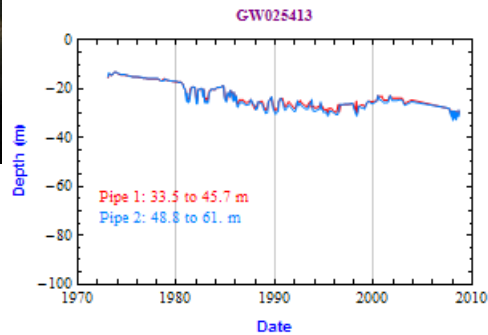


# Macquarie-Bogan Catchment Groundwater Hydrographs

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August 2010



## Executive Summary

The hydrogeology of the Macquarie-Bogan Catchment has been studied extensively in the past 20 years, but there are still many gaps in our understanding of the groundwater systems and river-aquifer interactions. These gaps in our knowledge limit our capacity to manage water resources throughout the catchment. This document captures our current understanding of the hydrogeology of the catchment and provides a multidimensional spatial analysis of the groundwater monitoring bore standing water level (SWL) data. Based on the findings, recommendations for further research are presented.

Abstraction of groundwater for the purposes of irrigating cotton and other crops started in the Macquarie Catchment in 1967, and expanded until the turn of the century. To monitor the impact of groundwater usage NSW state water management departments installed monitoring bores in relevant zones. The groundwater monitoring data are publicly available on the Pinneena Groundwater Works CD. This report presents all the hydrographs for the Macquarie-Bogan Catchment, and examines the spatial and temporal trends displayed in these data. The primary goal of this report is to provide a graph of all the groundwater hydrographs in the catchment. A printout of the hydrograph set for 141 groundwater work locations within the Macquarie-Bogan Catchment is presented in the Appendix.

Through the implementation of water sharing plans there have been changes to groundwater allocations. At some locations there has been a reduction in the water allocated per share, with the aim of improving the long term viability of the groundwater resource for all users and the environment. The groundwater hydrographs provide a record of baseline conditions and can be used to assess the impact of variations in allocation and guide future management decisions.

Almost 40 years of groundwater hydrograph records enable long term groundwater level trends to be analysed throughout the alluvial regions of the catchment. Fluctuations in the groundwater level over long and short periods of time are analysed using traditional hydrograph plots and 3D plots to show the yearly and interdecadal impacts of groundwater extractions. The groundwater hydrograph data are interpreted in the context of existing geological knowledge, streamflow, rainfall and groundwater usage data.

Within the Macquarie-Bogan Catchment a balance needs to be achieved in the way water is managed if urban centres and farms dependent on the water are to prosper, while maintaining important wetlands at the end of the catchment. The Macquarie River flows northwest from the head waters on the western side of the Great Dividing Range just south of Bathurst, to join the Barwon River west of Brewarrina. The southern portion of the Macquarie River is highly regulated by Burrendong and Windamere Dams and by a series of weirs, bypass canals and irrigation channels that assist the diversion and abstraction of water for irrigation, industrial and domestic purposes. The major irrigation district is north of Narromine and south of the Macquarie Marshes on the fertile soils of the floodplain. This floodplain overlies up to 150 m of valley-fill sediments which lie within the Macquarie River palaeovalley. It is the fresh groundwater within these sediments and immediately underlying rocks that is used for irrigation. The Macquarie Marshes just north of the irrigation district are a large and diverse system of semi-permanent freshwater wetlands created by irregular flooding of the flat lands adjacent to the river and are an important ecological habitat.

This study identifies zones along the Macquarie River where aquifers within the sediments that fill the deep palaeovalley are locally hydraulically connected to the river, and zones where the deep aquifers are disconnected from the shallow aquifers and do not receive direct river recharge. The extent of the hydraulic connection between the alluvial aquifers and the immediate underlying sedimentary rock aquifers is poorly understood. The largest zone of groundwater depletion is west of Narromine, indicated by a series of monitoring bores that have slotted intervals 90 or more meters below the ground surface. This zone requires further

extensive hydrogeological and water chemistry investigations to better understand the recharge pathways. If the management goal is to reduce the decline in the groundwater level, then this region may require managed aquifer recharge.

North and west of Narromine there are zones of local rising watertable in the upper unconfined aquifer due to irrigation recharge (deep drainage). Further research is required to determine if this will result in future soil and water quality problems.

Based on these findings it is suggested that a detailed 3D lithofacies model needs to be constructed for the Lower Macquarie Alluvium groundwater management unit. This 3D model could then guide the construction of a coupled surface and sub-surface flow model. Also required is an extensive groundwater chemical investigation (with a focus on dating the ages of the groundwater zones) and coupled river and aquifer flow modelling, linked to the water chemistry investigations. The results of these investigations should help to better inform water management decisions.

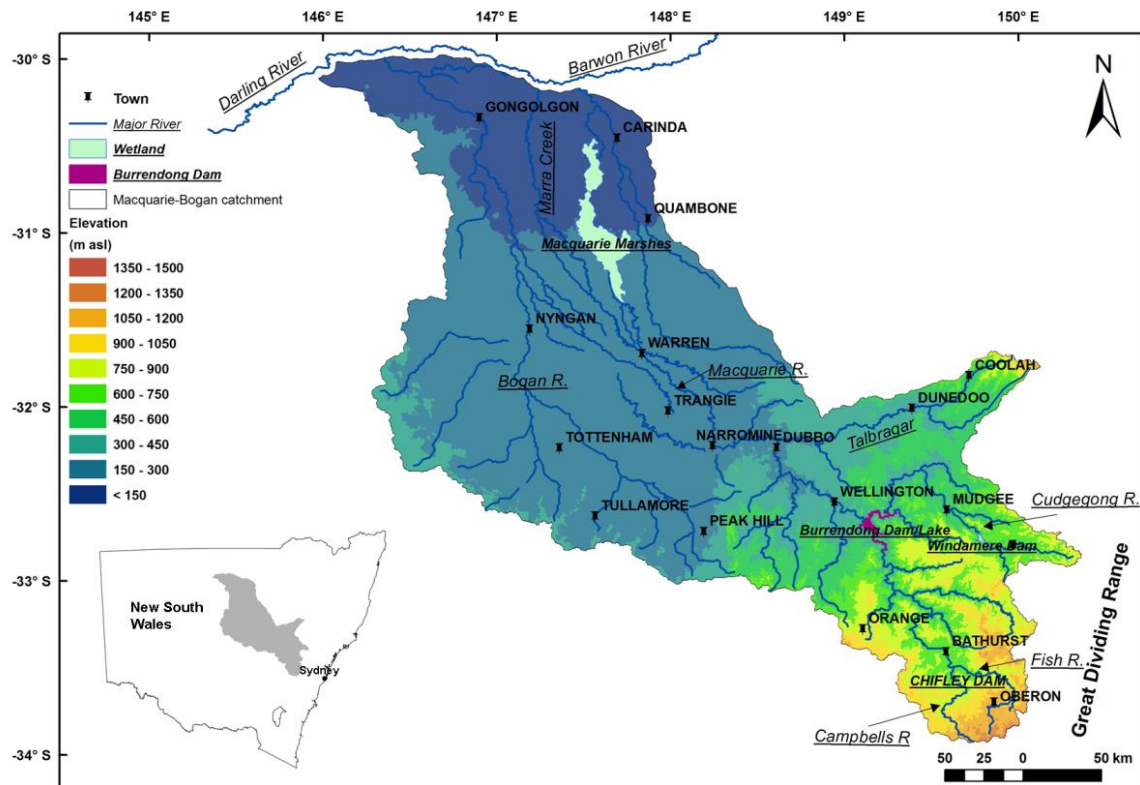
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## Introduction

This report reviews the historical groundwater measurements within the Macquarie-Bogan Catchment and assesses the spatial and temporal trends observed in these data in the context of the hydrogeology. The Macquarie-Bogan Catchment (covering 74,500 km<sup>2</sup>, about 7% of the total area of the Murray-Darling Basin (MDB)) is in central-west New South Wales. The catchment extends from the Great Dividing Range to its junction with the Barwon River (Figure 1). The major land use throughout the catchment is dryland pasture for livestock grazing. Wheat dominates the dryland cropping sector and cotton production generates most of the revenue from irrigated summer cropping and accounts for approximately 60% of consumptive water use in the catchment. Cotton growing began in this region in 1967 (<http://www.auscott.com.au/macquarie-valley/default.aspx>, 30 July 2010) and the area planted to cotton expanded up until the turn of the century. Most cotton is grown on the floodplain of the Macquarie River downstream of Narromine. However, there are irrigation areas further upstream and downstream and at the confluence of the Macquarie and Barwon Rivers (e.g. Carinda) (Herron et al., 2002). The irrigation farming in the lower Macquarie uses a combination of surface and ground water resources.

The Macquarie Marshes are a large and diverse system of semi-permanent, freshwater wetlands that are listed as a Ramsar site (declared 1986) under the – “Convention on Wetlands of International Importance” (<http://www.environment.nsw.gov.au/wetlands/RamsarWetlands.htm>, 2/Aug/2010). The nature reserve extends over an area of almost 18,143 hectares, approximately 10 % of the entire Macquarie Marshes floodplain (NSWNP, 1993; Hogendyk, 2007). The wetlands are created by irregular flooding of the flat lands adjacent to the meandering and braided stream network and are an important habitat for native plants and animals.



**Figure 1** - The Macquarie-Bogan Catchment. Topography, towns, main rivers and water bodies are shown.

## Hydrology

The Macquarie River is a tributary of the Barwon-Darling River. The neighbouring Bogan River and Bogan Catchment are coupled with the Macquarie for administrative purposes and water is diverted from the lower Macquarie River to the Bogan River (Figure 1).

The Macquarie River begins south of Bathurst at the confluence of the Fish and Campbells Rivers and drains the western side of the Great Dividing Range. The headwater in these subhumid uplands (highest altitude about 1400 m.a.s.l., Figure 1) and bedrock valleys provide most of the perennial discharge to the river. The river then descends through a bedrock-confined alluvial valley in its middle reaches below Burrendong Dam and Wellington (altitude 300-450 m.a.s.l.). Burrendong Dam is the main storage in the catchment supplying irrigation demands downstream to Oxley, as well as supplementing flows to the Macquarie Marshes located in the northern reaches of the catchment. Below Narromine the river debouches onto a semiarid alluvial floodplain-fan (altitude 200 - 300 m.a.s.l.) and there is a net loss to streamflow due to abstractions for irrigation, evaporation and losses to groundwater recharge (Herron et al., 2002).

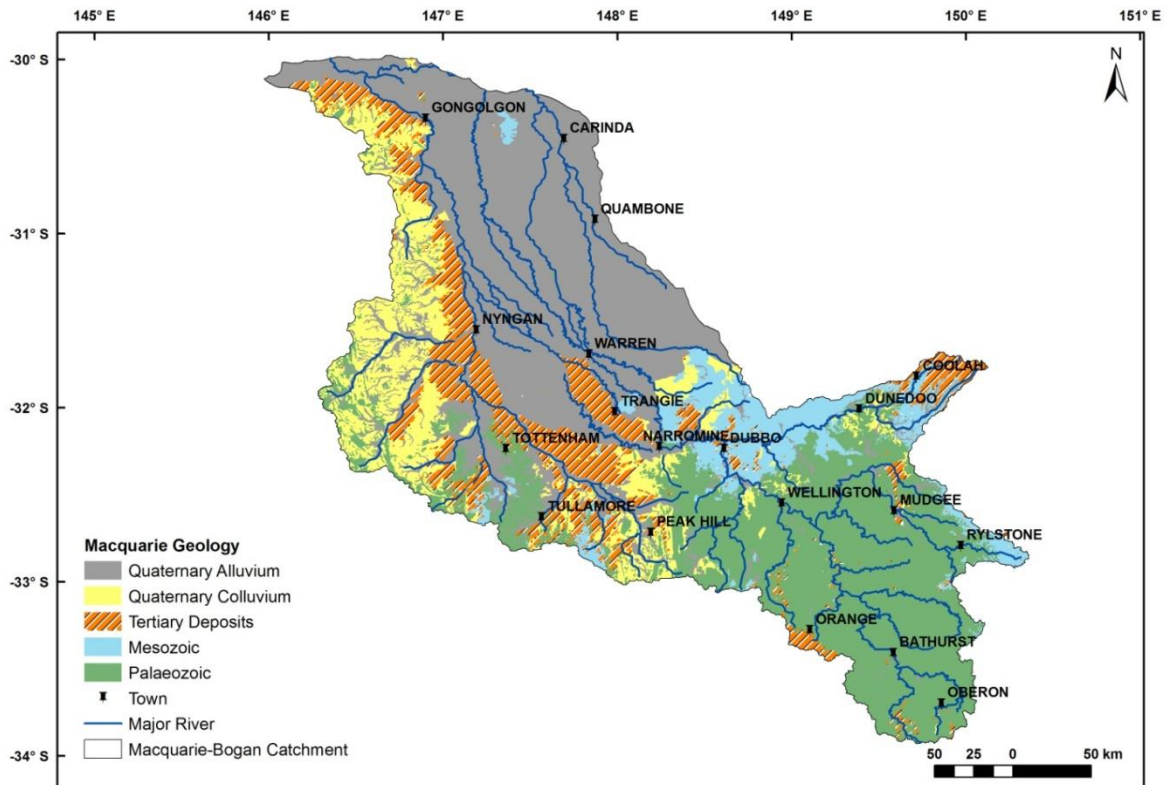
On the low-relief dryland alluvial fan plain the meandering single channel of the Macquarie River breaks down into a series of distributary channels with associated floodouts and floodplains in the Macquarie Marshes (Ralph et al., 2007; Yonge and Hesse, 2009; Ralph and Hesse, 2010). Water supplements have been allocated to the Marshes to ensure their ecological sustainability and the wetland receives predominantly winter-spring flood water from the Macquarie River. However, water resources development and river regulation have reduced the flooding frequency of the wetlands and the average volume of important inundation events (CSIRO, 2008) with ecological consequences (Kingsford and Thomas, 1995; Kingsford and Johnson, 1998; Kingsford, 2000).

Flows along the lower Macquarie River and into the Marshes have been regulated since 1896, when the first weir was built at Warren (Ralph and Hesse, 2010). Burrendong Dam, which controls the discharge along the lower reaches of the Macquarie River, was installed in 1967. Another irrigation storage dam, in the headwaters of the catchment, is Windamere Dam, upstream of Mudgee on the Cudgegong River (Figure 1). This dam was constructed in 1984 with the dual purpose of supplying water for a small irrigation industry in the Cudgegong River Valley and acts as a backup storage for Burrendong Dam. The flow is further controlled by a series of weirs, bypass canals and irrigation channels that assist the diversion and abstraction of water for industrial and domestic purposes.

Unregulated tributaries downstream of Burrendong Dam include the Bell, Little and Talbragar Rivers. Downstream of Warren, there are several anabranches departing from the Macquarie River channel, which either rejoin the Macquarie River or flow to the Bogan or Barwon Rivers (Figure 1).

## Hydrogeology

The Macquarie River Catchment consists of very gently sloping Cenozoic alluvial plains of the eastern Darling Riverine Plain (BRS, 2009). The Palaeozoic basement of the Lachlan Fold Belt outcrops in the west and south and it can be considered the hydraulic basement (Figure 2). Great Artesian Basin (GAB) sedimentary rocks underlie the alluvial-filled portion of the Macquarie-Bogan Catchment. The rocks are Early to Middle Mesozoic and are overlain by Late Mesozoic age rocks which form a confining layer over the GAB rocks. Upstream of Narromine the basement is Triassic while downstream it is Jurassic-Cretaceous (Martin, 1999). These rocks are overlain by the Cenozoic (Neogene-Quaternary) unconsolidated sediments which form the alluvial aquifer (Skelt et al., 2004). The majority of the groundwater monitoring data presented in this report relates to groundwater monitoring bores in the alluvial sediments, although some monitoring bores are located in the sedimentary rocks 90 to 150 m below the ground surface.



**Figure 2** - Geological map of Macquarie-Bogan Catchment (from Surface Geology map of Australia 1:1,000,000 scale, Geoscience Australia, modified).

The system of alluvial aquifers consists of an upper unconfined aquifer and lower semi-confined aquifers. The upper unconfined alluvial aquifer consists of very extensive, shallow alluvial fan sediments deposited by creeks draining the nearby highlands. It is generally composed of fining-upwards sequences, mainly sand and gravel with occurrence of confining beds (clay bands). Coarse-grained sediments are deposited in and near river channels and finer-grained sediments are deposited by flood waters, distal to the river channels.

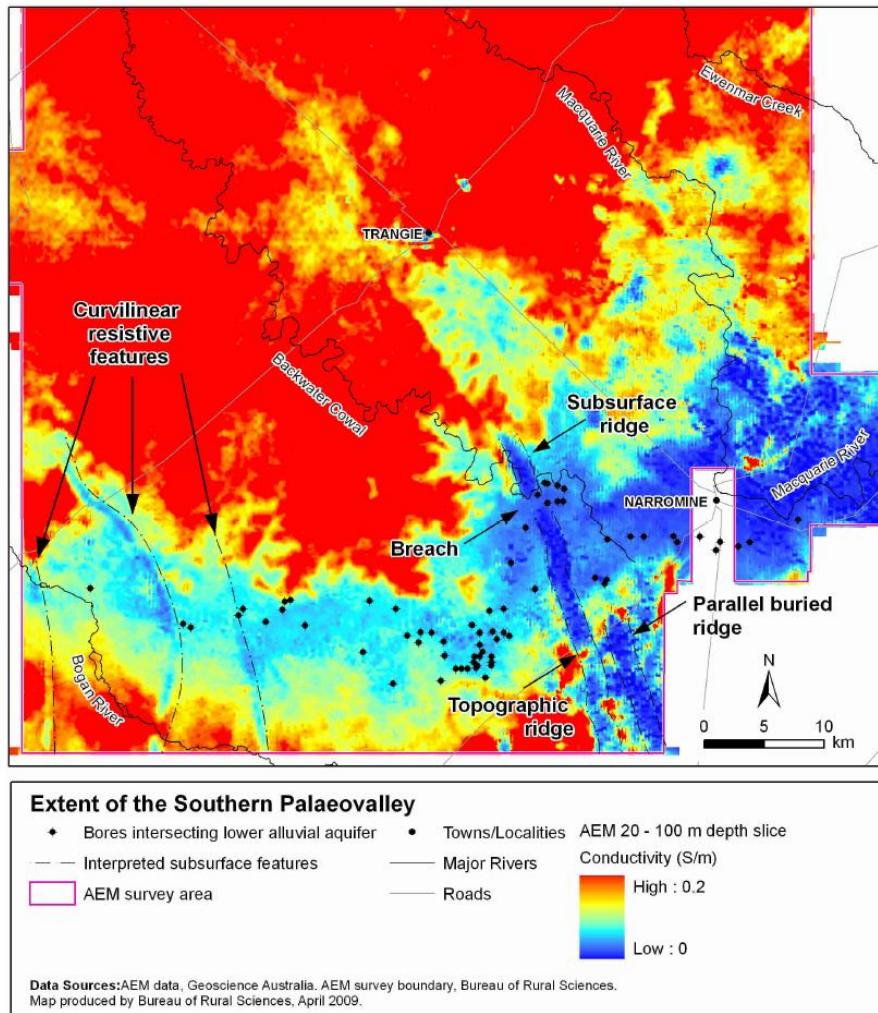
The lower semi-confined alluvial aquifers are restricted to the valley-fill sediments of the ‘Southern Palaeovalley’, which is a buried depression up to 140-160 m deep in the lower slopes and plain between Narromine and Dandaloo. This palaeovalley represents the proto-Macquarie River Valley, which was actively down-cutting an east to west valley until the Pleistocene, when the river switched to a northerly course at about where the town of Narromine now stands. The Bureau of Rural Science (2009) has mapped the Southern Palaeovalley using an airborne electromagnetic survey. The boundary of the palaeovalley has been enhanced by altering the AEM colour stretch to 0 – 0.2 S/m (Figure 3). This study highlights that the Southern Palaeovalley terminates against a buried ridge of Hervey Group Sandstone at Dandaloo, and does not swing northward to connect to the Macquarie Marshes. The geophysical survey also shows the presence of two parallel buried ridges of Hervey Group Sandstone lying 7 km apart in the south west of Narromine. These ridges are breached, but have caused the palaeovalley to narrow significantly. There is also a prominent topographic ridge 15 km south-west of Narromine which extends underground for 6 km in a north-north-west direction; it is buried beneath 20 to 25 m of Quaternary sediments and is breached to a depth of 80 m underneath the Backwater Cowal (Figure 3).

Based on the evolution of the Macquarie River Catchment described in Tomkins and Hesse (2003; 2004), the erosion of the valley basement in the Mid to Late Miocene was due to a substantial uplift of the highlands, synchronous with or shortly after widespread volcanism. Subsequently the palaeovalley was filled, in the Late

Miocene-Late Pliocene, by well sorted and rounded quartzose fine gravel and coarse sand. This older gravelly unit was then eroded and reworked in the Quaternary and a sandy clay unit, which forms the modern floodplain, was deposited. While valley incision can be viewed as a response to tectonism, the Pleistocene incision was instead due to reduced sediment supply resulting from a drier climate.

Stratigraphic palynology studies carried out in the Macquarie River Catchment by Martin (1994) show that most of the Neogene (Pliocene and Miocene) assemblages occur at relatively shallow depths, but west-southwest of Narromine, where the palaeovalley of the Macquarie River is located, they are found at greater depth of 100 m. Water within valley-fill sediments is the main source of groundwater in the catchment.

Further information about the palaeovalley origin and the litho and bio facies can be found in Martin (1999), Haridharan (2003), Tomkins and Hesse (2003; 2004), and BRS (2009).



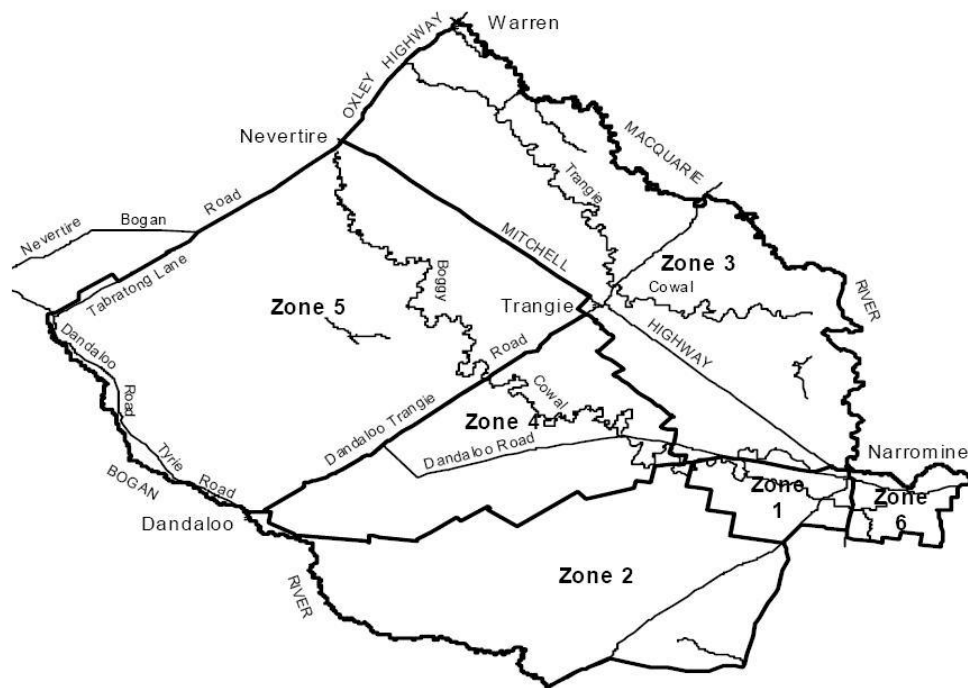
**Figure 3** – Airborne electromagnetic survey map of the Lower Macquarie district. The lateral extent of the Southern Palaeovalley is delineated by the east-west trending belt of sediments with low electrical conductivity (from BRS, 2009).

## Water Sharing Plans

Water Sharing Plans (WSP) for the lower Macquarie groundwater sources and for the Macquarie and Cudgegong regulated rivers water sources (<http://www.water.nsw.gov.au/Water-management/Water-sharing/Water-sharing/default.aspx>) have been introduced as a part of the New South Wales Water Management Act 2000, ([http://www.austlii.edu.au/au/legis/nsw/consol\\_act/wma2000166/](http://www.austlii.edu.au/au/legis/nsw/consol_act/wma2000166/), 2/Aug/2010) which requires the implementation of ten-year plans defining equitable water sharing arrangements between the environment and groundwater users (urban centres, stock and domestic farm supplies and irrigation supplies. Water management plans aim to achieve a balance between protection of the environment and sustainable use of water for both economic and social well-being.

The groundwater sharing plan took effect in the Lower Macquarie Alluvium groundwater management unit in October 2006 and runs until June 2017, when it will be revised. ([http://www.water.nsw.gov.au/Water-Licensing/About-licences/Which-Act-applies-/act\\_central/default.aspx](http://www.water.nsw.gov.au/Water-Licensing/About-licences/Which-Act-applies-/act_central/default.aspx), 2/Aug/2010). The groundwater plan covers the unconsolidated alluvial aquifers west of Narromine (DNR, 2003; Figure 4). A surface Water Sharing Plan for the Macquarie and Cudgegong Regulated Rivers Water Source commenced in July 2004, but was suspended in July 2007.

Due to historically low dam levels there has been limited access to surface water in the past decade. Seven of the last 10 years have had an announced allocation of less than 10%, and for the 06/07 and 09/10 seasons the announced allocations was 0% (<http://waterinfo.nsw.gov.au/ac/allocation.shtml>, 2/Aug/2010). Access to groundwater, within the limits of the water sharing plan, has been an important water resource during the drought years. Groundwater usage has remained at historically high levels during a period of limited recharge. The impact of using groundwater in a period of limited recharge and details on the volume of groundwater used are discussed below.



**Figure 4** - Groundwater management zones within the Lower Macquarie Alluvium groundwater management unit (from DNR, 2003).

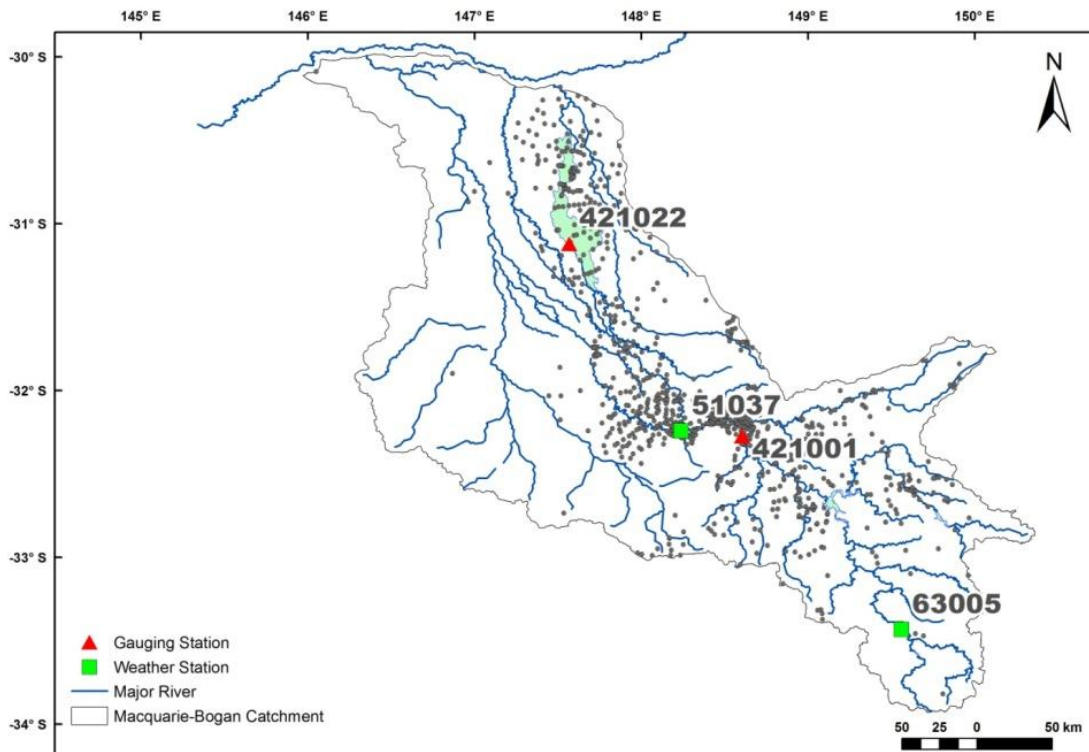
## Rainfall

Precipitation varies temporally and spatially within the Macquarie-Bogan Catchment. Mean annual rainfall varies from around 1000 mm in the headwaters, through the middle of the catchment (800-500 mm, Dent et al., 2007), to less than 400 mm at the end of the catchment (Herron et al., 2002) where the climate can be considered semi-arid. Bar charts of the monthly average rainfall for the weather station at Bathurst (station 63005, Figure 5) and Narromine (station 51037, Figure 5) are present in Figures 6A and 6B, respectively. Rainfall is generally higher in the summer months at both locations, and high in July at Narromine.

Trends in rainfall are highlighted by plotting the cumulative rainfall departure (CRD) curves for the Bathurst and Narromine rainfall data (Figure 7). A CRD graph is constructed by determining the mean rainfall using the complete record, finding the residual from the mean for each year (subtracting the mean value from the total yearly rainfall), and then keeping a tally of the residuals (Weber & Stewart, 2004). Downward slopes indicate periods of below normal precipitation and upward slopes indicate periods of above average precipitation.

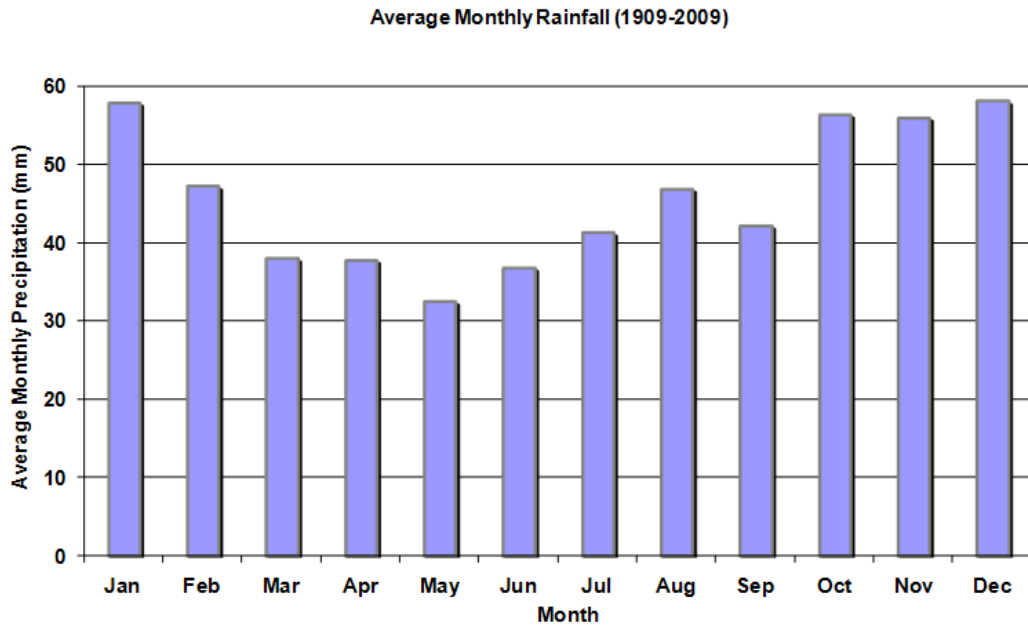
Although Bathurst is wetter than Narromine, the trends for rainfall are similar at both locations. The curves can be divided into two main periods. The first half of the 20<sup>th</sup> century was dry, and then there was wet run from the late 1940s until the late 1970s. For the past two decades rainfall has fluctuated around the average.

The 'dry phase' began in 1895 with a particularly severe drought from 1895 to 1902 that affected the whole of western NSW (Hogendyk, 2007) and throughout the first half of the twentieth century conditions continued to be basically dry. Much higher rainfall in the late 1940s marked the beginning of a 'wet phase' which lasted for three decades from 1947 to 1978. The drought years of 1979-82 started a second dry phase, which was followed by average rainfall based on the limited rainfall record.

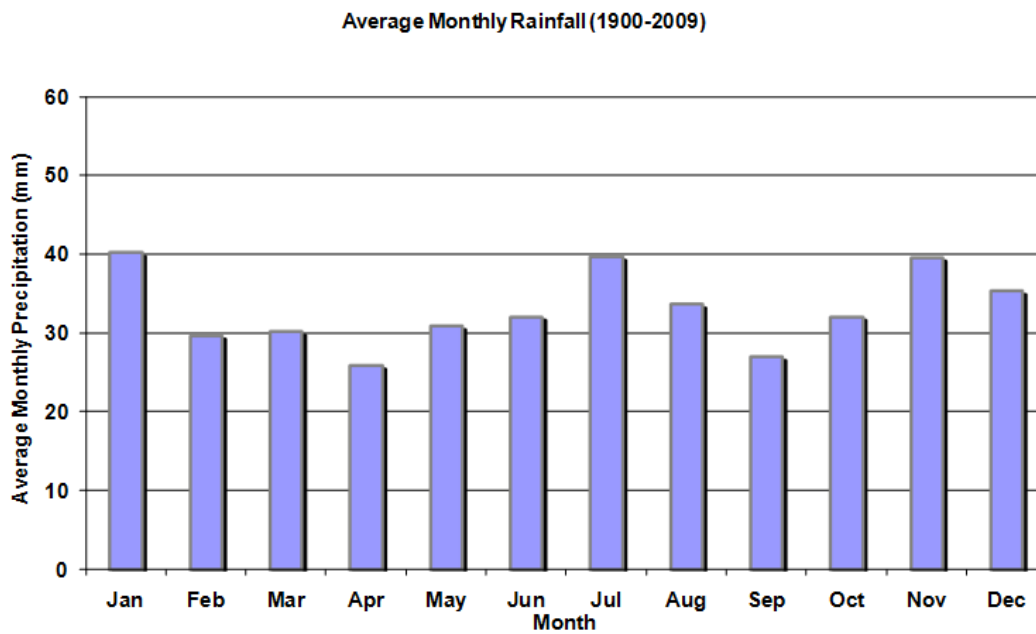


**Figure 5** - Location of monitoring bores (black spheres), gauging and weather stations used for this report.

A) Bathurst Rainfall

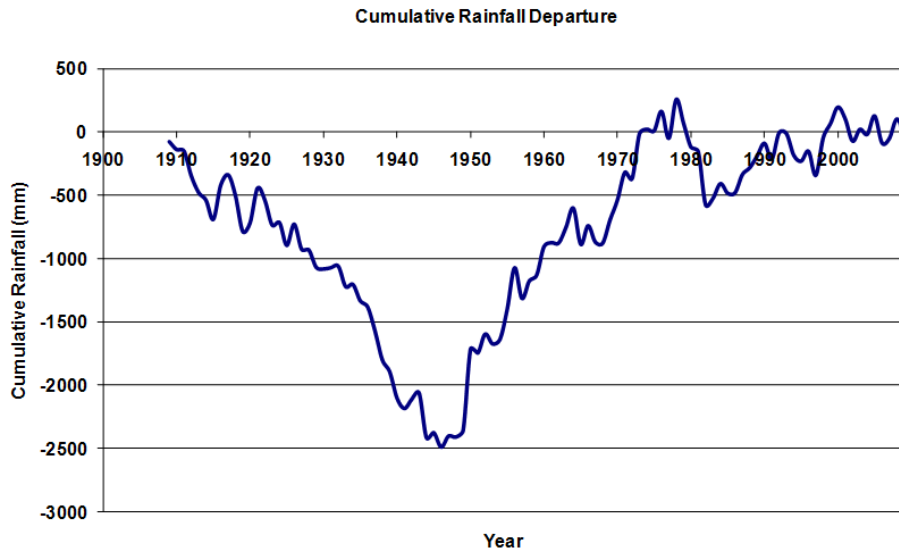


B) Narromine Rainfall

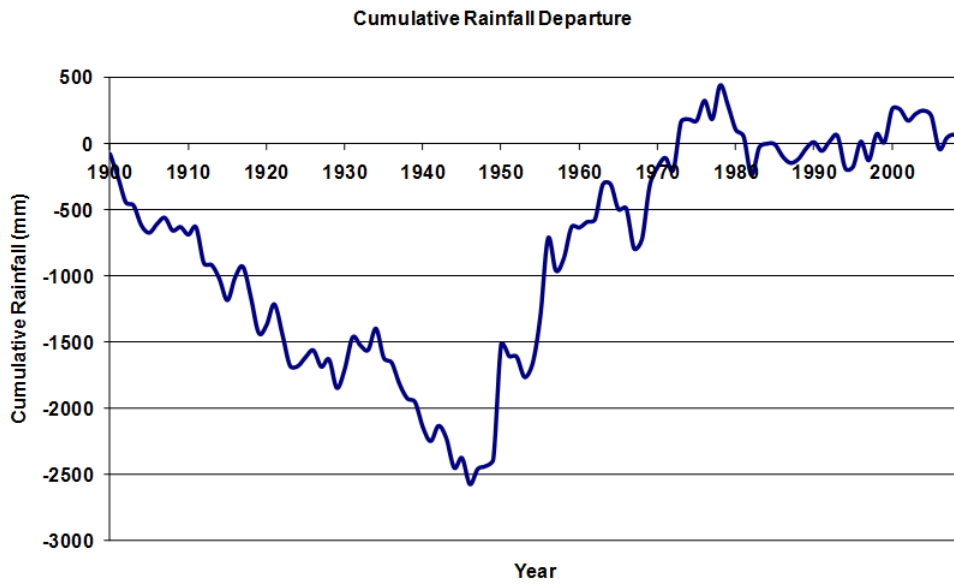


**Figure 6** – Bar charts of average monthly precipitation at A) Bathurst (station 63005) B) Narromine weather (station 51037). Climatic data are from the Bureau of Meteorology website (BOM, <http://www.bom.gov.au>).

A) Bathurst



B) Narromine



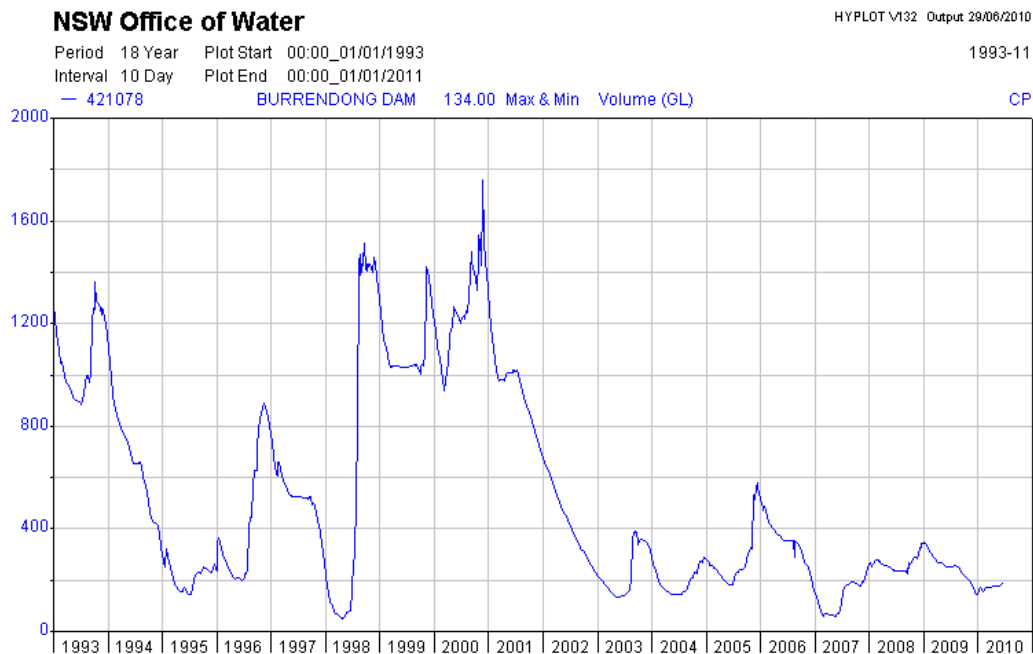
**Figure 7** - Cumulative rainfall departure curves calculated using rainfall data from A) Bathurst (station 63005) and B) Narromine (station 51037).

# Surface Water

## Burrendong Dam

Burrendong Dam is operated in conjunction with Windamere Dam to supply water to the Cudgegong and Macquarie valleys. Burrendong Dam is situated on the Macquarie River, just below its junction with the Cudgegong River, 30 km upstream from Wellington (Figure 1). The dam provides water for town water supplies, recreation, irrigation agriculture, industry, and environmental flows. Flows in the Macquarie River are highly regulated: Burrendong Dam regulates 91% of inflows and Windamere Dam regulates 94% of inflows. These two upstream dams capture high winter inflows (reducing winter flows downstream) and release water during summer for supply to downstream users (CSIRO, 2008). The dam also reduces the impact of flood waters from the upper catchment affecting towns and rural properties in the lower catchment. Burrendong Dam has a storage capacity of 1,188,000 ML. Figure 8 shows a time series of reservoir volume in storage (GL).

Although rainfall at both Bathurst and Narromine over the past two decades has fluctuated around average historical levels, inflow into Burrendong Dam has been well below the historical average since 2003. Since 2003 irrigators have had reduced or no access to dam water supplies. Historically surface water supplies have been the dominant water source for the irrigation sector in the Macquarie Catchment. This highlights the dependency of the irrigation industry on above average rainfall falling in the upper catchment.



**Figure 8** – Burrendong Dam gigalitres (GL) in storage (Data from NSW Office of Water, [http://waterinfo.nsw.gov.au/water.shtml?ppbm=STORAGE\\_SITE&da&3&dakm\\_url](http://waterinfo.nsw.gov.au/water.shtml?ppbm=STORAGE_SITE&da&3&dakm_url), 02/Aug/2010).

## *Streamflow*

Monthly hydrological streamflow data were obtained from NSW Office of Water (Pinneena 9.3 Continuous Monitoring DVD, <http://waterinfo.nsw.gov.au/pinneena/cm.shtml>, 2/Aug/2010 ) for two gauging stations on the lower Macquarie River: Dubbo (station 421001) and Oxley (station 421022) (Figure 5). The data were used to calculate monthly and total annual discharge volumes for both stations (Figures 9 and 10). Monthly flow peaks in August, prior to the start of the cotton growing season, and remains high until November (Figure 9). It can be observed in Figure 10 that since 1950 there has been a downward trend in the yearly discharge volume. Plots of the total monthly discharge at both streamflow gauging stations also show this trend (Figure 11). This trend will be analysed in more detail below.

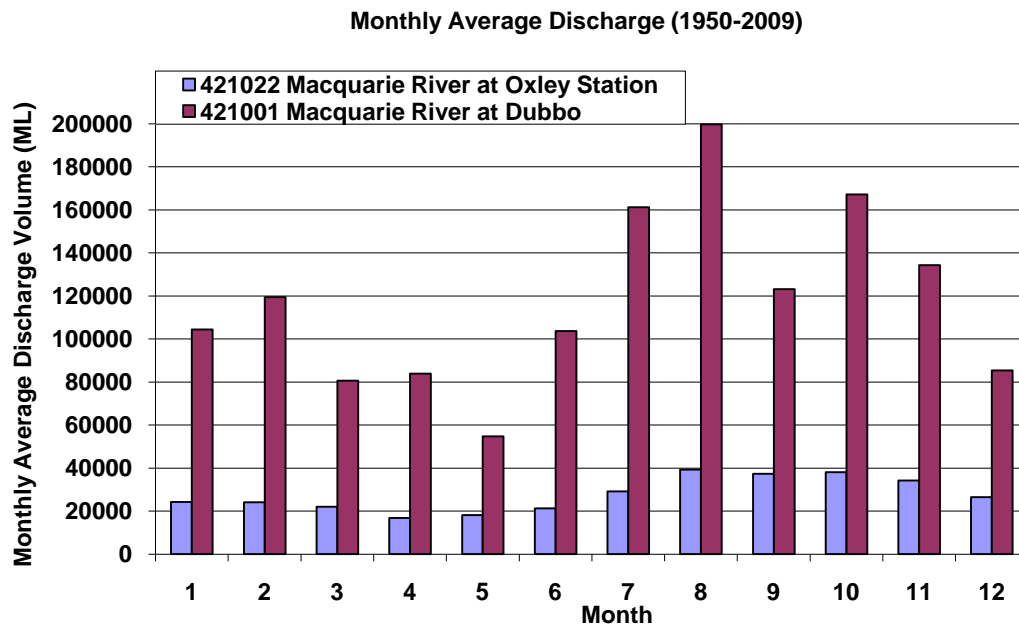
Like most inland Australian rivers, flow along the lower Macquarie River is irregular as clearly displayed by the longer hydrological records in Figure 11. Large floods occurred in 1950, 1952, 1955, 1956, 1973, 1978 and 1990 (DWR, 1991; Hogendyk, 2007). These are observable in the streamflow record at Dubbo (Figure 11A). The 1955 flood level in Dubbo was the highest ever recorded. Large floods are interspersed by medium and small flood events, with some periods of very low or even zero flow. Flood peaks are less extreme and less variable in the Oxley station (Figure 11B) further downstream where generally the discharge volume is one order of magnitude less than at Dubbo.

Large-scale river regulation has significantly altered the seasonality of streamflow and flow regime on the lower Macquarie River by reducing the frequency of large and medium sized floods; an analysis of pre- and post-Burrendong Dam flow records at Oxley station can be found in Brander (Brander, 1987). The effects of regulation and water resource developments on discharge at gauging stations located at Dubbo and Oxley are analysed in Ralph and Hesse (2010). Their analysis shows how the installation of Burrendong Dam in 1967 has changed the frequency and magnitude of flows. In that study a comparison of peak and mean monthly discharge of the Macquarie River at Dubbo and Oxley shows that the seasonality of flows has shifted from a winter to summer dominance.

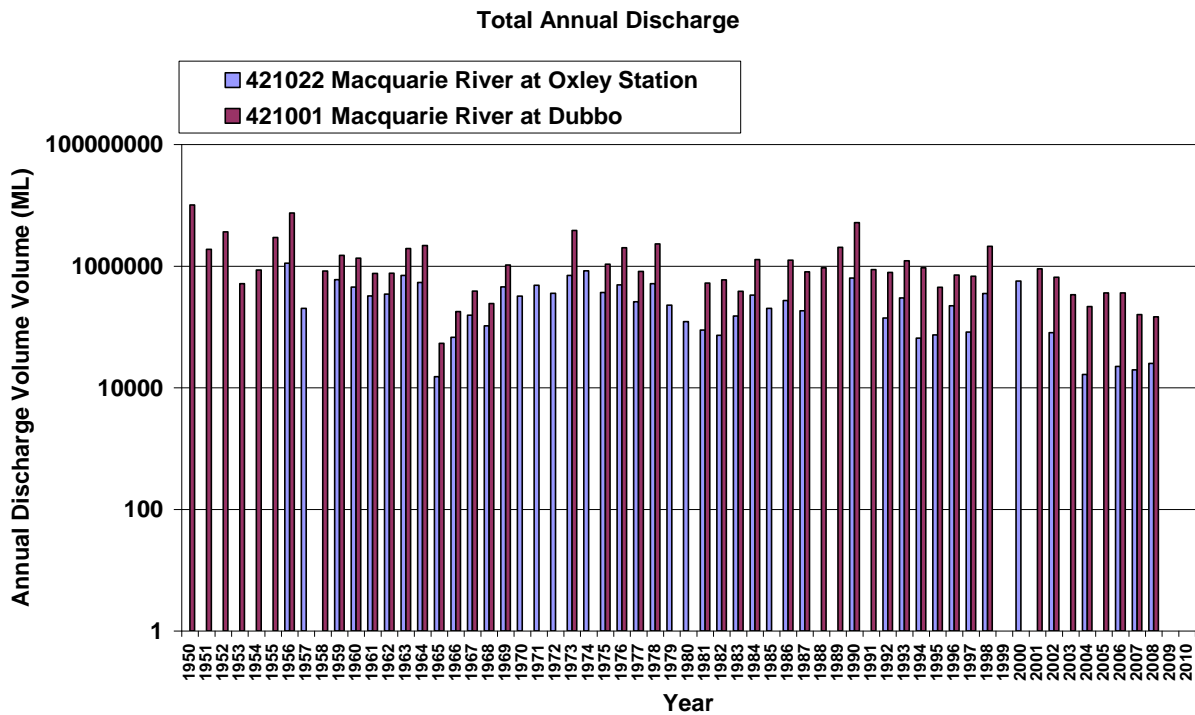
The 1990 flood peak shown in Figure 11A is a key event linking river and flood water recharge to the underlying aquifers. As will be shown below, this flood event is clearly observable in some of the groundwater hydrographs.

The Macquarie River streamflow data from the Dubbo and Oxley gauging stations were used to compare the amount of water entering this reach of the river at Dubbo with that leaving at Oxley (Figure 12). The ratio of the out/in for the period 1950 to 2009 is plotted in Figure 12. The outflow at the Oxley gauging station is on average 27% of the inflow at Dubbo. This loss is due to a combination of evaporation, river leakage to the underlying aquifers, and extractions for urban and irrigation supplies. Over the length of the record there has been a slight increase in the loss between Dubbo and Oxley. This decrease is consistent with the increased use of groundwater within the region, but a more detailed volumetric and statistical analysis is required to confirm the link. Within the graphs it is apparent that other oscillations in the ratio occur. Further work is required to understand the physical processes that cause the oscillations. During the last half of the past decade (corresponding to reduced irrigation water availability from Burrendong Dam), and reduced streamflow recorded at Dubbo, the ratio has increased.

Cumulative departure curves were calculated for the discharge volumes at Dubbo and Oxley. This method highlights above or below average flow trends (indicated by positive and negative slopes, respectively) in the streamflow data. The cumulative streamflow discharge departure (CSDD) curve for Dubbo is plotted with the upstream rainfall CRD curve for Bathurst (Figure 13A) and the streamflow CSDD at Oxley is plotted with the CRD rainfall curve from Narromine (Figure 13B). The CRD rainfall graphs in Figure 13 have been calculated over the same interval as the streamflow data (1950-2009).

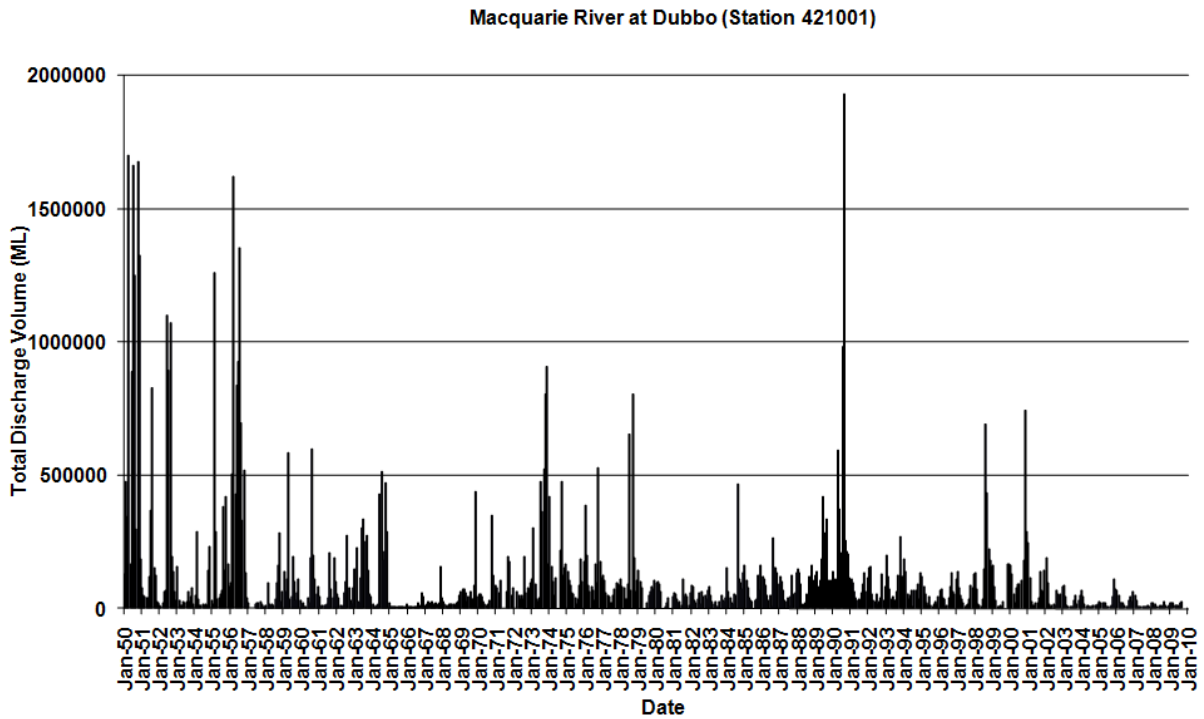


**Figure 9** - Monthly average discharge volume of the Macquarie River at Dubbo and Oxley gauging stations over the period 1950-2009 (data from the Pinneena Continuous Monitoring version 9.3 DVD, NSW Office of Water).

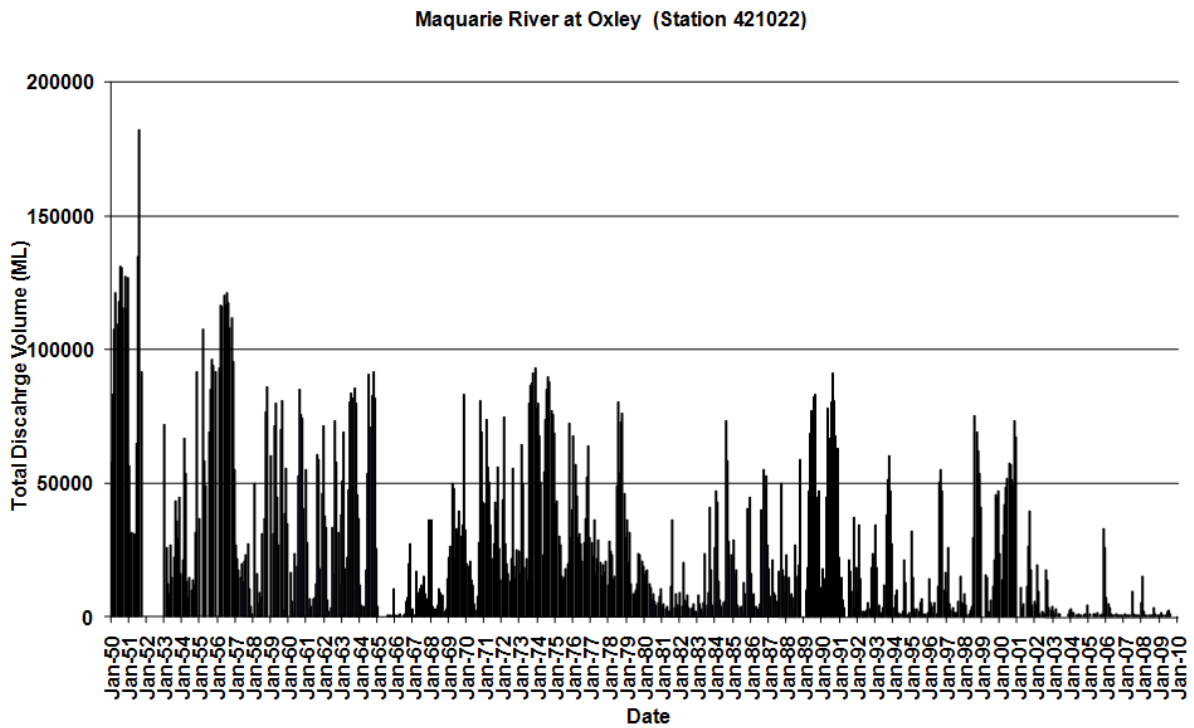


**Figure 10** - Total annual discharge volume (in ML/year) of the Macquarie River at Dubbo and Oxley gauging stations from 1950 to 2008. (Note logarithmic scale).

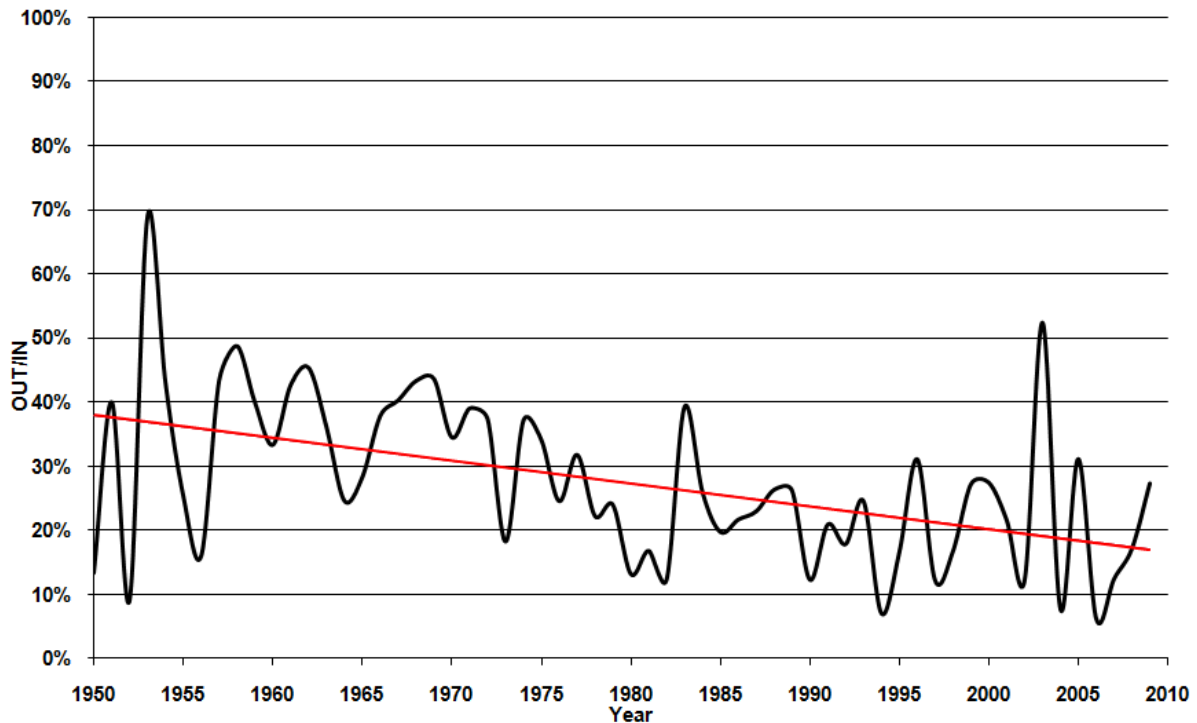
A)



B)



**Figure 11** - Total monthly discharge of the Macquarie River at Dubbo (A) and Oxley (B) gauging station for the period 1950 to 2010. (Note: different scales in the graphs: discharge at Oxley Station is an order of magnitude smaller than that at Dubbo).



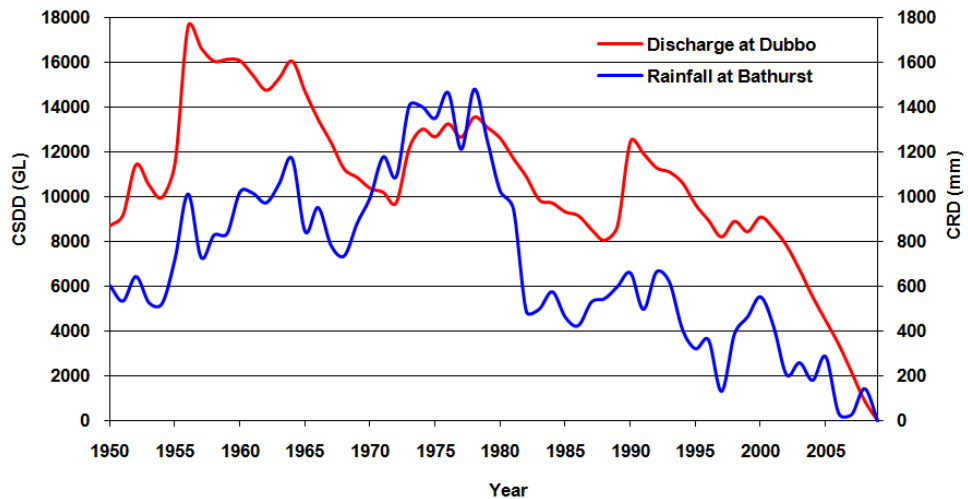
**Figure 12** – Ratio of the flow out/in (as a percentage) along the reach of the Macquarie River between Dubbo (in) and Oxley (out) for the years 1950 to 2009.

Gaps in streamflow datasets were filled using monthly average values calculated over the whole period (1950-2009) and reported above in Figure 9. Data from nearby gauging stations were not used because the discharge volume can vary between stations. The use of averaged values can be considered adequate for the purpose of the present report. However more advanced statistical methods could be applied, such as the Markov chain method (Meyn and Tweedie, 1993; Grayson et al., 1996), which is a discrete random process with the property that a data value depends on its previous value (or state) for one or more earlier values in the time series. Gyau-Boakye and Schultz (1994) presented a comprehensive review of several methods that can be used for supplementing missing data or filling gaps in flow series. The applications of these methods was beyond the scope of this project, but should be applied in detailed streamflow investigations. Annual flow models based on annual rainfall data were also built for Dubbo and Oxley gauging stations and presented as a continuous series in Ren et al. (2009); in that paper a complete period of annual flow records was reconstructed based on available annual rainfall data for the period 1879-2006.

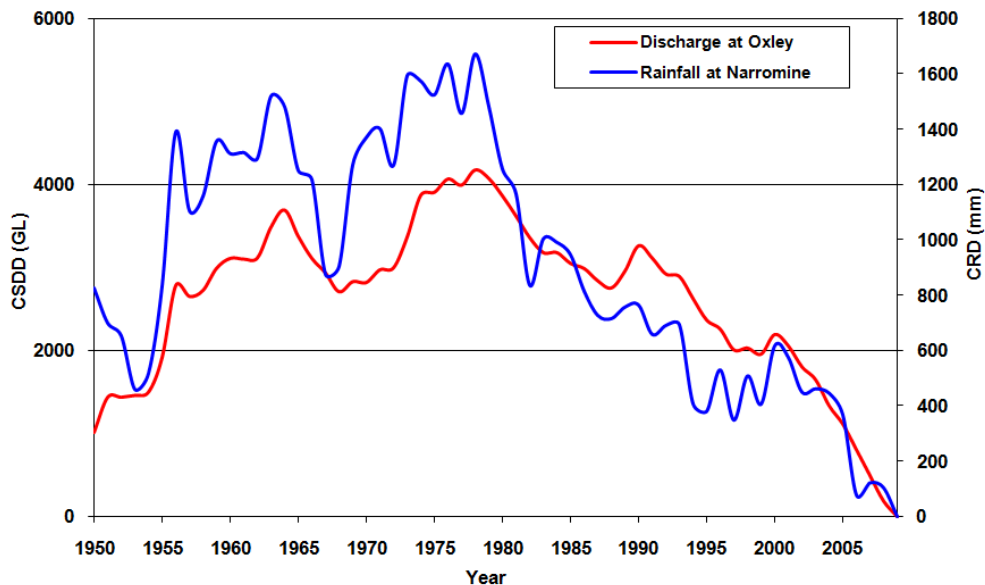
Both graphs in Figure 13 show a strong correlation between rainfall and streamflow, which is to be expected. Each line in graphs A and B has a relative high starting value, due to the fact that 1950 was a flood year. A positive trend is then shown in all four curves from 1950 until the early 1960s. This indicates wetter than average conditions. From the late 1970s all curves display a negative trend indicating drier than average conditions for the statistical period (1950 to 2009).

After Burrendong Dam was completed in 1967 the flood mitigation capabilities of the dam were called upon almost continuously throughout the wet 1970s. During the 1970s there are steep positive slopes in the CRD curves, but dampened responses in the CSDD curves, as both streamflow gauging stations are downstream of Burrendong.

A)



B)

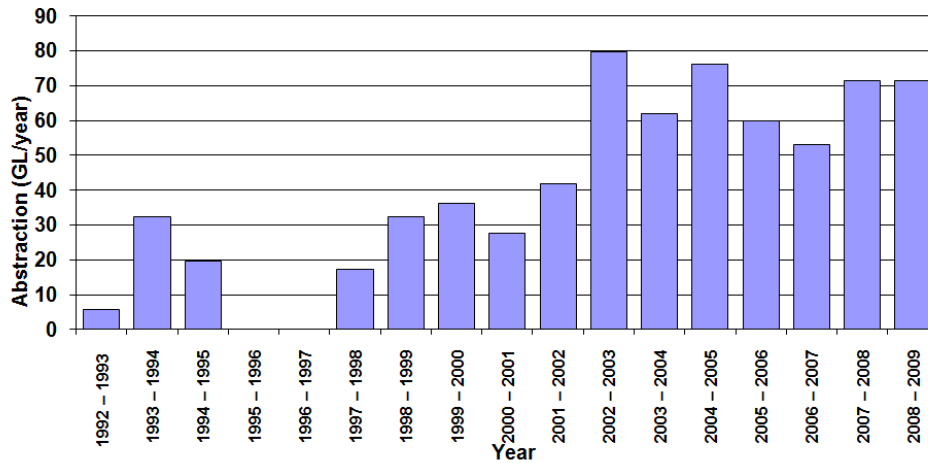


**Figure 13** – Comparison of the cumulative streamflow discharge departure (CSDD) at and the cumulative rainfall departure (CRD) curves for Dubbo streamflow and Bathurst rainfall (A) and Oxley streamflow and Narromine rainfall (B).

## Groundwater

### *Groundwater Usage*

Significant groundwater abstraction occurs for stock, irrigation and town uses upstream of the Macquarie Marshes, and north of Narromine. The Macquarie region uses slightly less than 4% of the surface water diverted for irrigation in the MDB and groundwater use is about 11% of the MDB total (CSIRO, 2008). Figure 14 shows the yearly groundwater use (GL/year) within the Macquarie-Bogan Catchment for the period 1992 to 2009. Between 20 and 30 GL/yr of good quality groundwater is extracted from the Southern Palaeovalley aquifer for irrigation (BRS, 2009).



**Figure 14** - Total yearly groundwater usage in the Macquarie-Bogan Catchment (Data provided by the NSW Office of Water; data for years 1995-1996 and 1996-1997 not available).

### ***Groundwater Hydrograph Data***

The groundwater hydrograph data were obtained from the NSW Groundwater Database Pinneena CD 2009 v 3.1 (<http://waterinfo.nsw.gov.au/pinneena/gw.shtml>, 2/Aug/2010). A subset of the information from the CD was extracted for all bores within the Macquarie-Bogan Catchment boundary.

The Macquarie database includes:

- the location of approximately 12,596 bores (all types: stock, domestic, irrigation etc);
- construction details and methods of bores and pipe;
- drillers logs;
- extended groundwater levels for 141 groundwater monitoring locations;
- purpose and use information for each bore; and
- the water bearing zone.

Bores that had suspected errors (sudden jumps in water levels, zero reading etc) were removed from the 3D analysis of the hydrograph data. Groundwater hydrograph sets with minor errors (spikes in years not analysed) were used. Further quality control is needed, but was beyond the scope of the project. It is expected that such an extensive database would have errors, given that the data have been collected over several decades, were manually measured, manually entered into the database, and transferred between various databases. The majority of the data are sufficient for examining the major spatial and temporal trends recorded in the groundwater monitoring bore standing water level. The SWL is typically measured from the top of the casing to the top of the water within the pipe (units, metres below the casing top). The terms groundwater head and groundwater level are used when the SWL is converted to a height above the Australian height datum (units, metres above sea level).

Mathematica (<http://www.wolfram.com/>) scripts were written to extract the information from the database. At each groundwater works location there can be one or more holes. Within each hole there can be one or more pipes. Each pipe can have one or more slotted intervals. On the hydrographs the highest and lowest levels reported were used to indicate the total length of the aquifer for which the groundwater level was being measured. For some bores the slotted interval information was not on the Pinneena CD or the information was ambiguous. For such cases the information was not added to the hydrograph plots. Comprehensive details on

the Mathematica scripts are given in Kelly et al. (2010). In the 3D plots below the data were plotted at the midpoint of the slotted interval(s).

Plotting the absolute fluctuation or relative difference over time in 3D at the midpoint of each pipe's slotted interval requires no assumptions about assigning the screened section of a bore to a specific aquifer. The 3D analysis is then used to assign each pipe to an aquifer.

### Bore Hydrographs

Variability in the SWL was examined both spatially and temporally over two time periods. Connectivity throughout the aquifer systems and the impact of pumping were examined by looking at the extent of SWL fluctuation recorded in a year (Figure 15). The long term trends were examined by determining the relative difference in the recovered SWL between 1988 and 2008 (Figure 16). The relative difference is determined using the recovered SWL reading for the year, which is taken to be the SWL measurement recorded just prior to the start of the irrigation season. This is typically recorded in June or July.

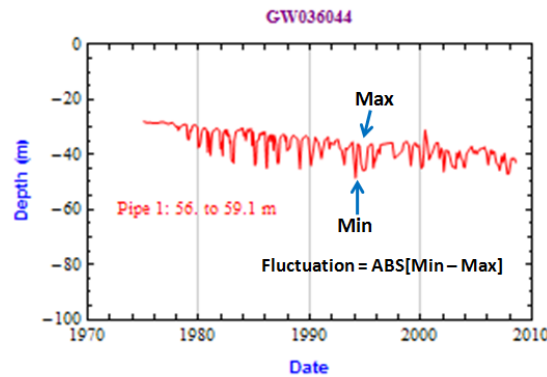


Figure 15 – Method for determining the standing water level fluctuation for a year.

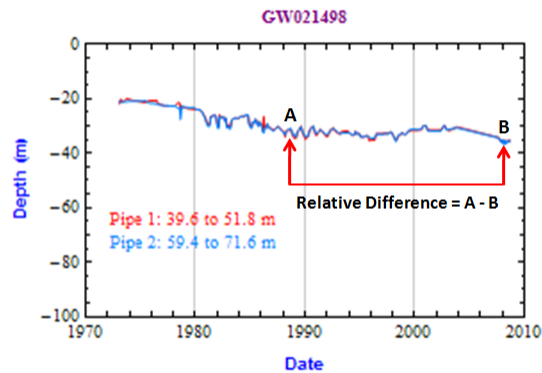


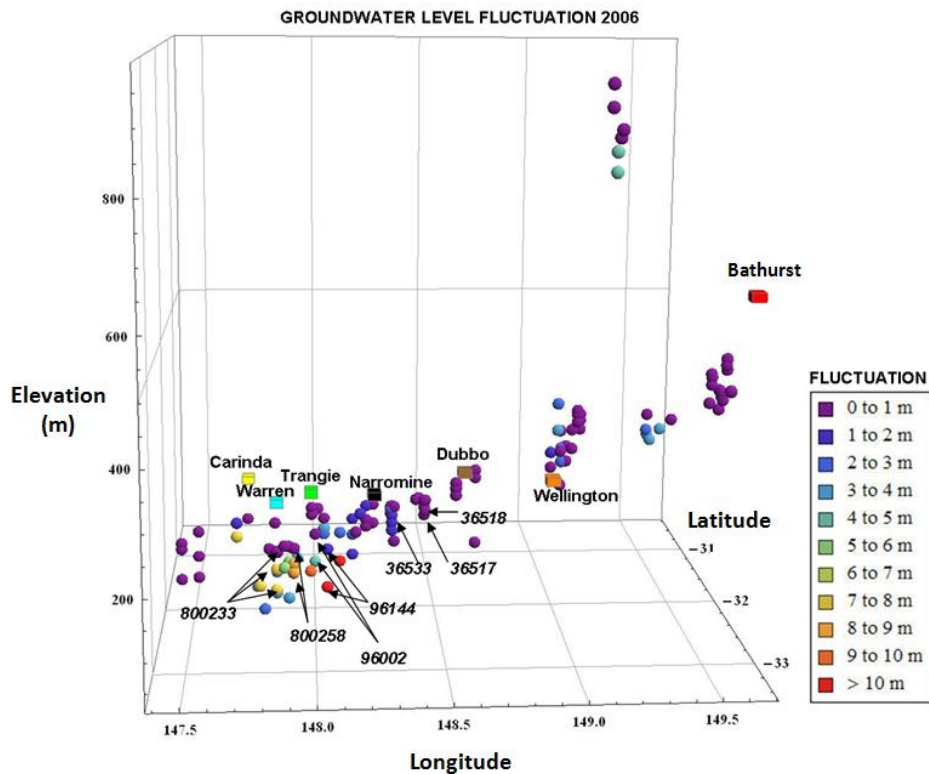
Figure 16 – Method for determining the relative difference in the recovered standing water level recorded in the monitoring bore.

### Short Term Head Fluctuation Analysis

Fluctuations in the SWL were analysed over a time span of one year in order to understand how the aquifer system responds to seasonal pumping stress. The year 2006 was selected for analysis because this was a year when most sites were measured, there were no floods, the yearly rainfall was low (270 mm of rainfall recorded at the Narromine weather station) and groundwater usage was reasonably high (Figure 14). The maximum difference in the SWL within one year for each groundwater monitoring pipe was plotted in 3D at the midpoint of the slotted interval(s) (Figure 17).

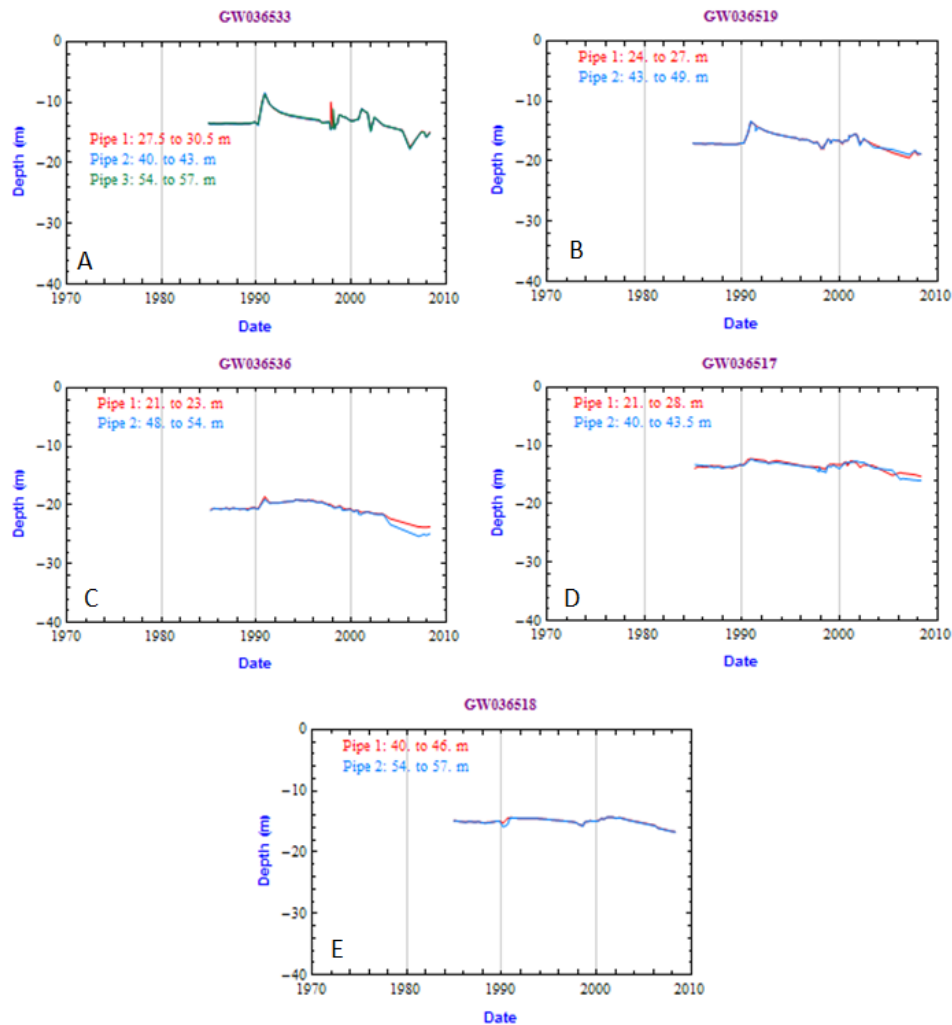
As the aquifer is stressed due to groundwater extraction the groundwater head is reduced near the point of extraction. The longer a pump runs the larger the zone that is affected. Monitoring bores (pipes) near a groundwater bore pump detect this change in groundwater head, which is reflected as changes in the SWL recorded in the monitoring bores. The groundwater head surrounding a pump changes laterally and vertically. If there is a layer that impedes the flow of water and pressure transfer (for example a clay layer), between the pump at depth and the ground surface, then the groundwater head will only change at depth. On the other hand, if the system is hydraulically connected at all levels of the saturated sedimentary sequence, pumping will result in a groundwater head change at all depths as the pressure transfer will be distributed throughout all depths (of the saturated sedimentary sequence).

Figure 17 shows the SWL fluctuation due to pumping stresses for the year 2006. For most of the Macquarie-Bogan Catchment the SWL only fluctuates from 0 to 3 m (purple and blue spheres). The 3D plot of the SWL fluctuation shows some areas of hydraulic connection throughout all levels of the alluvial sequence. These areas are indicated by groundwater work locations where the spheres have the same colour at all depths.



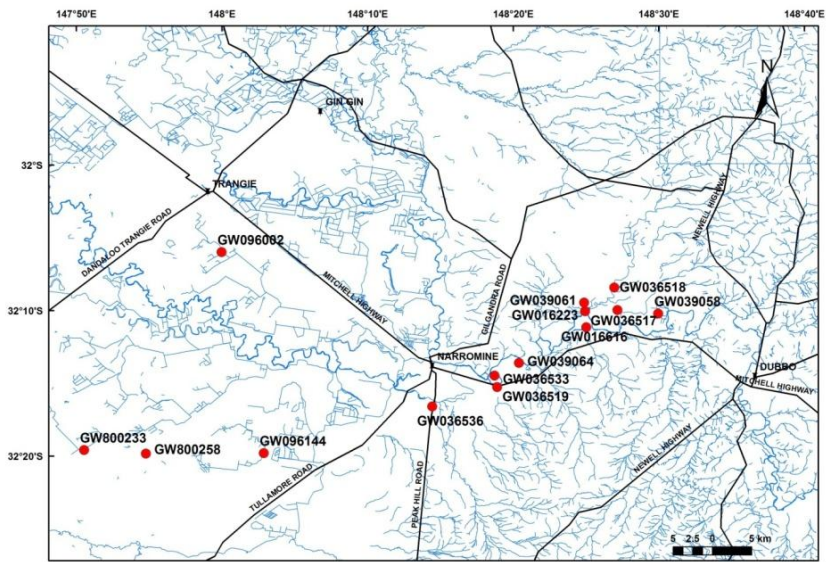
**Figure 17** – Absolute fluctuation recorded in the standing water level in 2006. The data points are plotted in 3D at the midpoint of the slotted interval of each monitoring bore.

Data in Figure 17 and hydrographs in Figure 18 confirm the presence of vertical hydraulic connectivity south-east of Narromine to a depth of at least 50 m (refer to Figure 19 for bore locations). This was also noted in the study carried out by the Bureau of Rural Sciences (BRS, 2009). Between Narromine and Dubbo the saturated aquifer system appears to be locally hydraulically connected to the river, which is the main source of recharge. Many bores in this area show a flood response in their hydrographs, indicating good hydraulic connection to the river and floodway recharge zones. Groundwater works sites GW036533, GW036519, GW036536, GW036517 and GW036518 in Figure 18(A-E) are good examples of hydrographs that show a response to the flood in 1990. In the Appendix GW016223, GW016616, GW039058, GW039061 and GW39064 also show a response to the floods in the 1970s (1973 and 1978) and 1990.

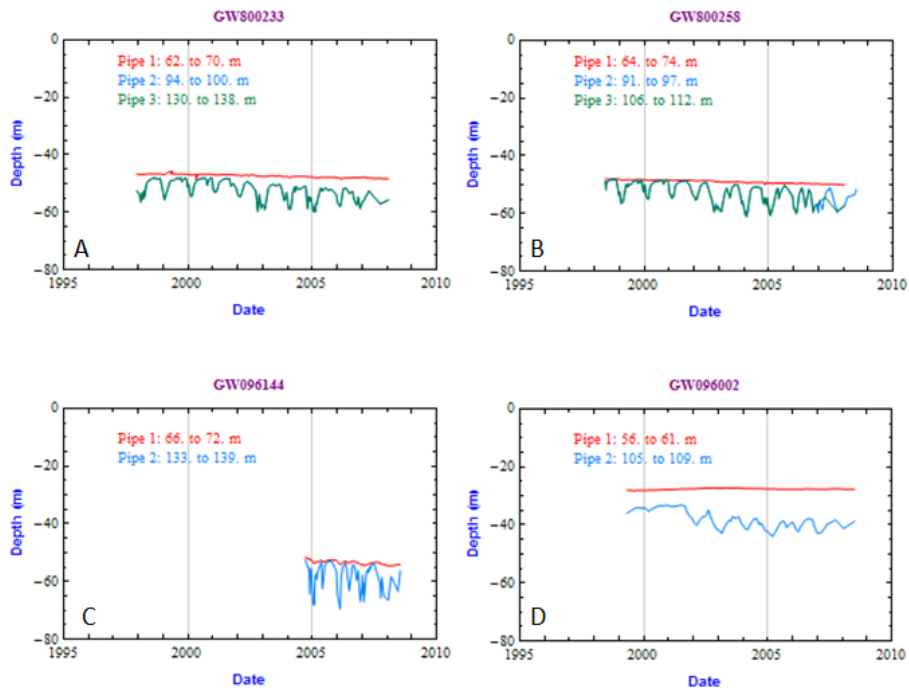


**Figure 18** - Bore hydrographs at locations GW036533 (A), GW036519 (B), GW036536 (C), GW036517 (D), and GW036518 (E). These hydrographs indicate a vertical hydraulic connection between the shallow and deep intervals of the aquifer system, because they show similar responses to the groundwater abstraction stress. Hydrographs A-E also display connection to the river, indicated by the flood response peaks (The 1990 flood peak is clearly observable in all hydrographs).

West of Narromine, and south of Trangie (Figure 19), where the Southern Palaeochannel is located (Figure 3), the responses of deep and shallow portions of the aquifer system to the pumping stresses are different. In this area the fluctuation data show 0-1 m absolute fluctuation for the year 2006 in the upper aquifer (purple spheres in Figure 17, red lines in Figure 20) and up to 8-10 m of absolute fluctuation in the deep semi-confined aquifer system (yellow and red spheres in Figure 17, and green and blue lines in Figure 20). The subtle downward trends of the near surface hydrographs over the past decade indicate that there is some leakage from the unconfined aquifer to the semi-confined aquifer system (Figure 20). A detailed lithofacies model and a new water chemistry investigation, including dating with isotopes, coupled with a surface and sub-surface flow model is required for this region to better quantify the extent of recharge.



**Figure 19** – Key bores between Dubbo, Narromine and Trangie. Bores between Dubbo and Narromine show good connection between the shallow and deep aquifers and connection with the river (refer to hydrographs in Figure 18) while bores west of Narromine indicate the presence of a confining layer between the shallow aquifer and the deeper semi-confined aquifer system (see hydrographs in Figure 20).



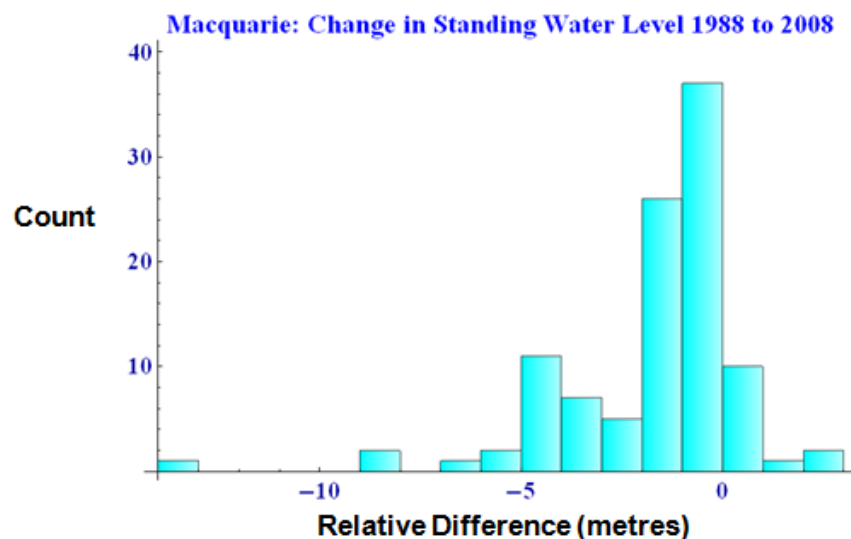
**Figure 20** - Bore hydrographs at locations GW800233 (A), GW800258 (B), GW096144 (C), and GW096002 (D). The slotted intervals associated with the red hydrograph lines are located in aquifers nearer the ground surface, which are isolated from the deeper semi-confined aquifers from which the groundwater is being abstracted. The pumping impact is indicated by the fluctuating blue and green lines in the hydrographs.

## Long Term Trends in the Standing Water Level

To analyse the long term impact of groundwater extraction and to detect any decline in the recovered SWL, the difference between the 1988 and 2008 recovered SWL was computed. This interval of time was selected to get a balance between the length of the record and coverage across the catchment. The recovered SWL is the level recorded throughout the year closest to the ground surface (excluding flood years) and usually occurs in June or July before the beginning of the pumping season, which typically runs from late August until February. Recovery of the SWL is important for the health and functioning of the aquifer and for the economic benefit of its users. During the pumping season the SWL drops, and if usage is in balance with recharge the SWL recovers to the level of pre-development over time (sometimes this requires a flood recharge event). If the SWL falls over time this indicates that usage is in excess of recharge for that time period.

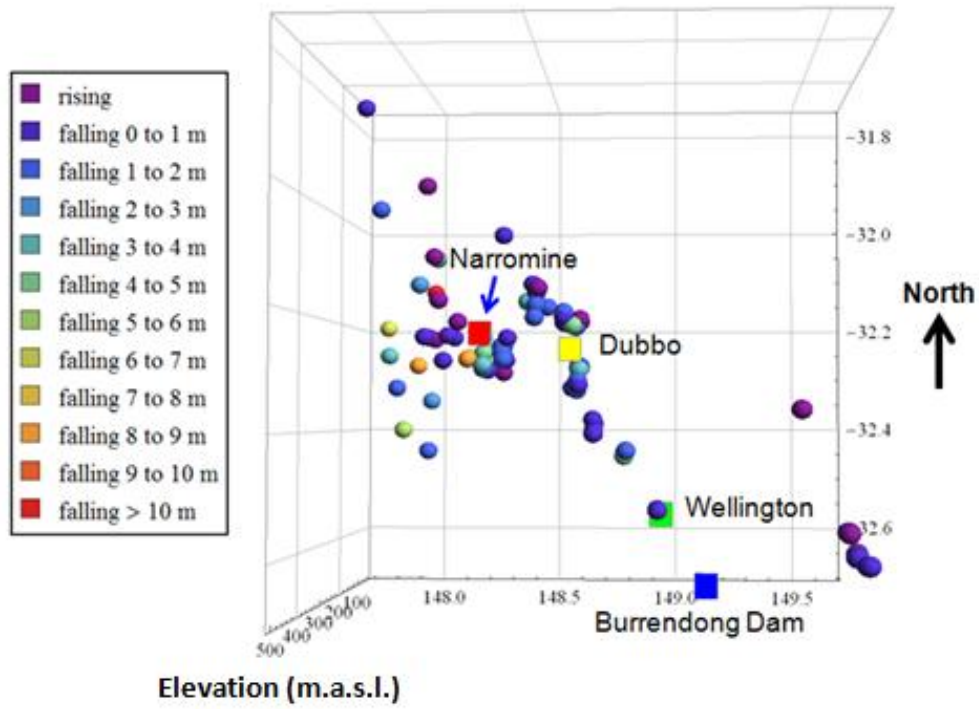
The relative difference in the SWL was determined for each location (Figure 16), tabulated in a histogram (Figure 21) and plotted in 3D at the midpoint of the slotted interval (Figure 22). At the majority of the groundwater monitoring locations the SWL has declined between 0 to 2 m (Figure 21). The largest fall in the SWL is 13.57 m. The maximum rise in the SWL was approximately 3 m. To gain a spatial understanding of the changes the relative difference in the SWL between 1988 and 2008 were plotted in 3D (Figure 22). Most of the bores in the shallow aquifer between Burrendong and Dubbo show little change (dark blue spheres). At depth only 6 pipes between Dubbo and Wellington show that the SWL has fallen between 3 to 6 m (light blue and green spheres). The region with the largest decline in the SWL is west of Narromine (orange and red spheres).

In Figure 22 the purple spheres indicate a rise in the SWL. There are 3 locations between Dubbo and Narromine where the SWL has risen, and there is a cluster of monitoring sites where the SWL is rising north-west of Narromine. It is not possible from the SWL measurement alone to determine if the rise in the SWL is due to a damaged pipe, or due to physical changes in the surrounding water pressure. This can only be determined from a site inspection.



**Figure 21** - Histogram of the relative difference in the standing water level between 1998 and 2008 for groundwater monitoring bores in the Macquarie-Bogan Catchment. Negative values indicate falling standing water levels.

A) Overhead View



B) Side View Looking North

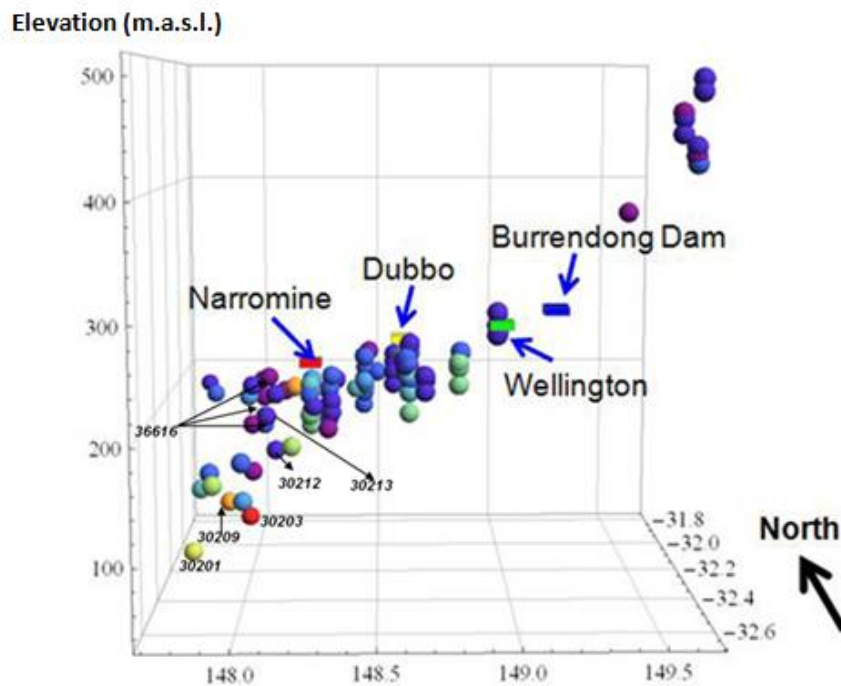
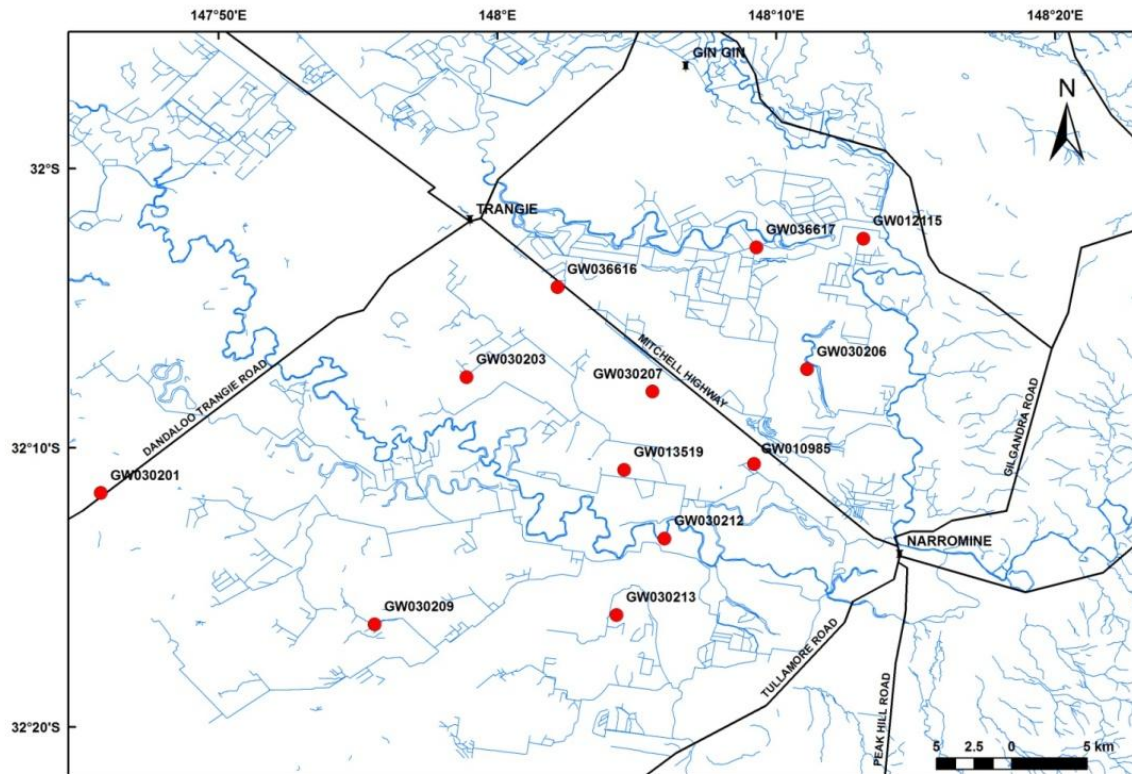


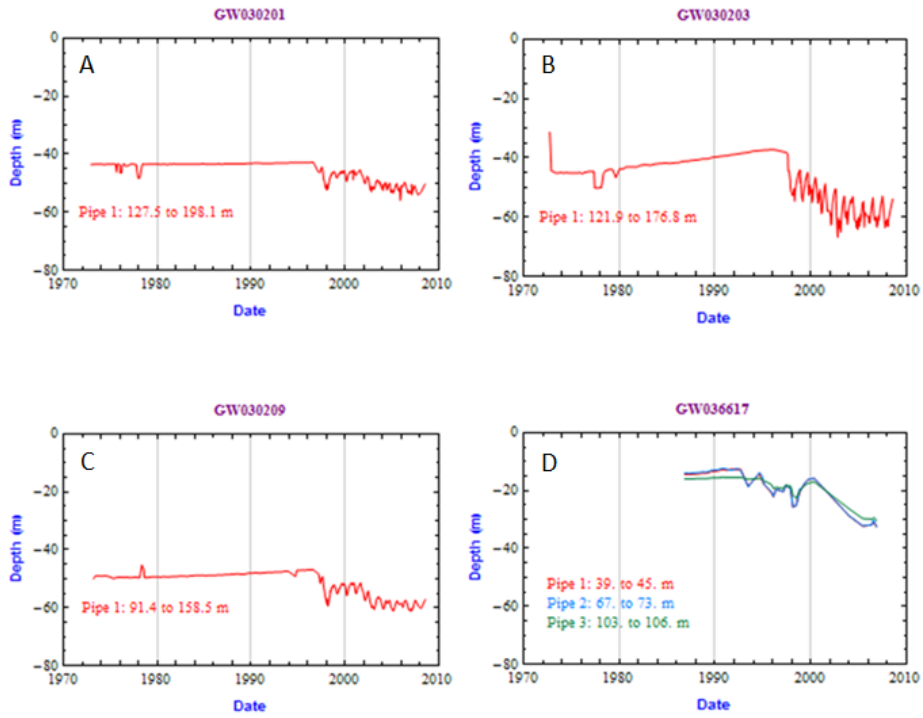
Figure 22 – Relative difference (1988 – 2008) in the groundwater monitoring bore recovered standing water level.



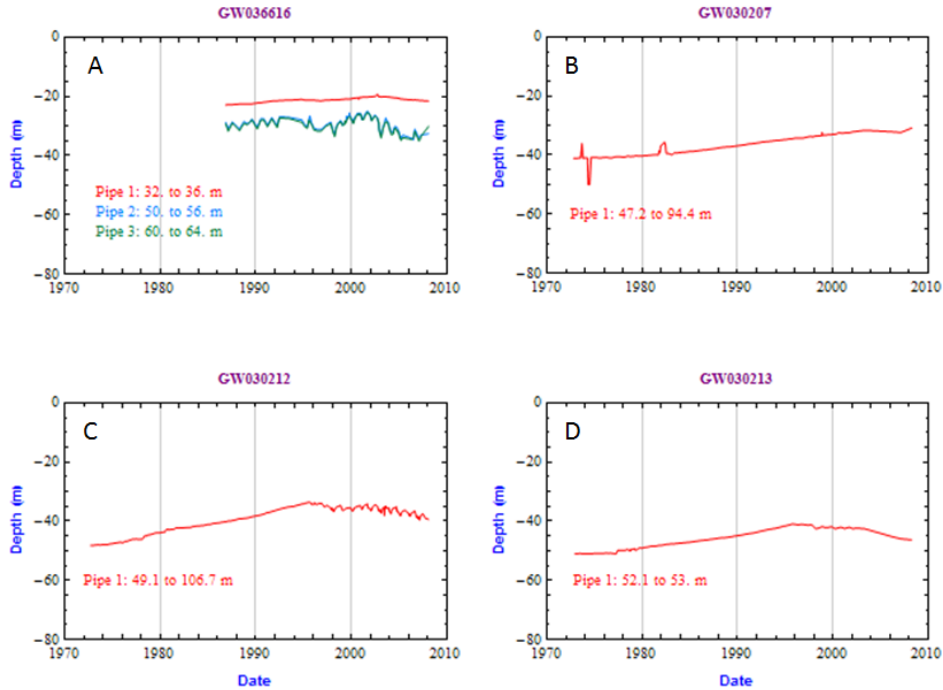
**Figure 23** – Key bores in the area between Narromine and Trangie. The groundwater hydrographs at these locations are present in Figures 24 and 25.

In the Lower Macquarie Alluvium groundwater management unit (Figure 4) bores GW030201, GW030203, GW030209, GW036617 (locations Figure 23, groundwater hydrographs Figure 24) show the largest decline in the SWL for the Macquarie-Bogan Catchment. Monitoring locations GW030201 and GW030209 (both on the edge of zone 4) show the clear impact of irrigation abstractions starting in 1997. The beginning of irrigation activity is highlighted by the change from smooth to fluctuating lines in the hydrographs. Since 1997 groundwater abstraction near these monitoring bores has been in excess of recharge. These monitoring bores are both slotted at depths greater than 90 m. Despite being some 15 km apart they display very similar patterns of decline, which indicates good hydraulic connectivity throughout this portion of the sedimentary sequence. As shown in Figure 20, there is some leakage from the upper unconfined aquifer to the semi-confined aquifer in this region. Monitoring location GW030203 is in zone 4. The pattern of decline does not indicate a direct link to GW030201, which is in the same zone. There is no response to the 1990 flood waters moving along the Macquarie River in these deep distal monitoring bores (which is to be expected given the distance to the river). Monitoring bore GW036617 is closer to the Macquarie River, near the Trangie Cowl, and despite its proximity to the flood pathways, the aquifer system below 60 is not being recharged at a rate to balance abstraction.

Rising SWL (Figure 24) in the Lower Macquarie Alluvium is clearly apparent in the hydrographs around the 1980s. Several areas of rising watertable are located between the towns of Narromine, Trangie and Gin Gin, corresponding to zone 1 and the southern part of zone 3 of the Lower Macquarie Alluvium groundwater management unit. Deep drainage beneath furrow irrigated crops is believed to be the primary source of water recharging the unconfined aquifer (Willis and Black, 1996; Willis et al., 1997). Initially the water table was rising at these locations at approximately 0.25 m per year, but since the mid 1990s the SWL has stabilised (Figure 25 sites GW036616, GW30212 and GW030213).



**Figure 24** – Bore hydrographs at location GW030201 (A), GW030203 (B), GW030209 (C), GW036617 (D). These hydrographs indicate depressurising of the deep aquifer system. Refer to map in Figure 23 for bore locations.



**Figure 25** - Bore hydrographs at location GW036616 (A), GW030207 (B), GW030212 (C), GW030213 (D). These hydrographs indicate a rising groundwater table. Refer to map in Figure 23 for the bore locations.

## Conclusions

Groundwater hydrographs provide important insights into the effect of groundwater extractions and irrigation on water resources and the subsequent impact on the environment. Almost 40 years of groundwater hydrograph records enable long term SWL trends (both spatial and temporal) to be analysed throughout the alluvial regions of the catchment.

Relative variations in the SWL analysed in the 3D plots and in association with the groundwater hydrograph plots show that along the reach of the Macquarie River between Narromine and Dubbo, the aquifer within the deep palaeovalley is locally hydraulically connected to the river, which is the main source of recharge. Groundwater hydrographs in this interval show simultaneous responses at all depths to either pumping stress or flood waters. In this reach of the Macquarie River the groundwater hydrographs indicate river recharge into the Southern Palaeovalley. Moving further west in management zones 2 and 4 the groundwater hydrographs indicate that there is an upper unconfined aquifer overlying a semi-confined aquifer system.

The long term (1988 to 2008) relative difference in the groundwater monitoring bore SWL analysis shows the impact of groundwater extraction in the lower aquifer. Depressurising of the aquifer has occurred in zones 4 and 2 of the Lower Macquarie Alluvium where the majority of groundwater has been extracted. Here the monitoring bore hydrographs show that, since pumping started the SWL has not recovered to the level of pre-development over time. Nor has a new equilibrium been reached with respect to the present level of groundwater abstraction, as the decline in the SWL has not stabilised. The largest decline in the SWL in the Macquarie-Bogan Catchment is in the Lower Macquarie Alluvium groundwater management unit. Between 1988 and 2008 the SWL at location GW030203 fell 13.57 m. This region requires further extensive hydrogeological and water chemistry investigations to better understand the recharge pathways and rates of water ingress. If the management goal is to reduce the decline in the SWL, then this region may require managed aquifer recharge.

Also shown in the relative difference SWL 3D plots and the bore hydrograph plots is an area of rising groundwater in the shallow aquifer between the towns of Narromine, Trangie and Gin Gin (zone 1 and southern part of zone 3 of the Lower Macquarie Alluvium groundwater management unit). Increased groundwater recharge and the rising watertable are due to increased deep percolation rates, most likely related to irrigation deep drainage (Willis and Black, 1996; Willis et al., 1997). Excessive deep drainage from irrigating crops could eventually result in the mobilisation of stored salts in the soil profile. This has already been observed in some irrigation districts throughout the Murray-Darling Basin (Watson, 1986; Slavich, 1992). Further research is required to determine if this will result in future soil and water quality problems. At some locations the rise in the unconfined water table appears to have stabilised.

A 3D geological model could be built using core logs data available from NSW PINNEENA CD 2009 and would enhance the understanding of the alluvial aquifer geometry, highlighting possible buried bedrock highs which could act as hydraulic impediments for flood and river recharge. The two parallel buried ridges and the topographic ridge south-west of Narromine identified by Bureau of Rural Sciences (2009) are examples of chokes which impede groundwater through-flow. These sorts of structures can have serious implications for the sustainable management of the groundwater resources. Groundwater is clearly being extracted at a rate higher than recharge in the region west of Narromine. This region needs detailed investigations to better understand from where and at what rate the deeper semi-confined aquifers are being recharged.

Dams regulate almost 93% of inflows and this sort of regulation has significantly altered the seasonality of streamflow and flow regime by reducing the frequency of large and medium sized floods that could otherwise recharge the aquifer and raise the groundwater level. Only when flooding rains occur downstream of Burrendong Dam is the Macquarie River likely to overflow its banks and to recharge the shallow alluvial aquifer

via the floodway recharge zones. Significant recharge is now restricted to a narrow band near the Macquarie River.

Analysis of the stream hydrographs at Dubbo and Oxley indicate that on average 27% of the streamflow is lost along this reach of the Macquarie River. In the groundwater hydrographs presented in this report there is a lack of detail to quantify how much of this loss is due to groundwater recharge. Given the resolution of the data, the only time recharge is apparent in the groundwater hydrographs is when there is a major flood flow along the Macquarie.

Over the last decade while Dam releases, streamflow and flood recharge have been at historically low levels, groundwater usage has stayed near historically high levels. For extraction bores that are near and hydraulically connected to the Macquarie River this must be maximising the leakage from the river to the underlying aquifers. This process cannot be inferred from the groundwater hydrographs alone. A more extensive stream-aquifer water balance study is required to quantify the extent of surface and sub-surface coupling. For bores several kilometres away from the river the aquifer system is being depressurised.

If the management goal is to not deplete the aquifers, and river and aquifer interactions are to be balanced with environmental goals, then surface and ground water need to be managed as one resource. We also need to have a good understanding of the hydraulic connections throughout the catchment, and how to balance the variable inputs with the outputs. For the Macquarie Catchment there already exist several water balance models (Dent et al. 2007; CSIRO, 2008) that demonstrate a moderate ability to predict groundwater responses for variable rainfall, river flow, flooding, and usage. To advance our knowledge of river and aquifer connectivity, and connectivity throughout the aquifer system, we must interpret the groundwater hydrographs in the context of a comprehensive 3D lithofacies model supported by extensive chemical investigations, examining both the major ion chemistry and dating the ages of the groundwater zones.

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## Appendix

All hydrographs within the Macquarie-Bogan Catchment are presented below for groundwater work locations for which there was a good data set and contained a least 80 measurements. There are records for 911 groundwater work locations within the catchment, but after quality control checks and removing bores with short data series the number has been reduced to a total of 141 good groundwater monitoring locations. All hydrographs are plotted at the same x and y scale to facilitate comparison. The y-axis depth is metres below the casing top. The monitoring interval printed on the graphs takes into account all slots and screens reported for a pipe. For example, if 3 slotted intervals are reported for a pipe then the lowest value represents the top of the 1<sup>st</sup> slotted interval, closest to the ground surface, and the highest value is the maximum depth reported for the 3<sup>rd</sup> slotted interval in the pipe. Before any management or personal decisions are made based on these graphs the reader is advised to personally check the primary data collated on the "Historic data CD "PINNEENA" for Groundwater Works": <http://waterinfo.nsw.gov.au/pinneena/gw.shtml>

