Three Dimensional Modelling of the Jemalong and Lake Cowal Aquifer Systems: Aims and Objectives

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ABSTRACT This paper describes research on groundwater systems and salinisation processes in the Jemalong and Wyldes Plains Irrigation District (JWPID), Lake Cowal and Bland Creek sub-catchment. It aims to predict potential areas at risk of salinisation. One of the main objectives of this research is to develop a three-dimensional groundwater flow model for the study area using MODFLOW and PEST softwares. The calibrated model will be used to quantify various groundwater balance components and to simulate a range of management strategies for conjunctive use of surface and groundwater resources in order to satisfy various demands in the study area and to minimise the risk of land salinisation. This paper characterises the study area, climate, surface hydrology, salinity and the hydrogeology of the study area. It is found that recharge of the watertable aquifer occurs from irrigation, Lachlan River and Warroo Channel.

1. INTRODUCTION

The Lachlan Catchment, the third largest catchment in the Murray-Darling Basin, is situated in the central west of New South Wales. In recent years, there has been an increasing incidence of salinity in the catchment. The Jemalong and Wyldes Plains Irrigation District (JWPID), located between Forbes and Condobolin, is threatened with rising watertables and salinisation. Several studies have been undertaken in the area with conflicting conclusions about the contribution of irrigation to groundwater recharge and salinisation processes. Estimates suggest that irrigation water adds 49 td^{-1} of salts to the district. Moderate to severe salinisation in the district has already occurred on the central Warroo, Bogandillon Swamp and isolated sections along the irrigation channel system. The Department of Land and Water Conservation [1997] estimated that around 50% of the dryland area and 4% of the irrigated lands in the district had soil electrical conductivity (EC) levels greater than 2,000 $\mu S\ cm^{-1}$ in 1995. Management of this irrigation area and salinisation occurring in its western part requires that the contributions of all processes impacting on the groundwater dynamics and salinisation be clearly identified.

The goal of this research is to investigate the groundwater systems and salinisation processes in the JWPID, Lake Cowal and Bland Creek sub-catchment and to predict potential areas of salinisation. Specific objectives of the research are to: (1) investigate the hydrogeological features of the aquifer system in the study area; (2) investigate the interaction of the aquifer system with the Lachlan River, Lake Cowal, Bland Creek and the irrigation system; (3) investigate the dominant salinisation processes; (4) develop and calibrate a numerical model of the aquifer systems; (5) use the calibrated model to examine watertable rise, interactions between aquifers, surface water and the irrigation system; and (6) develop best management strategies for conjunctive use of surface and groundwater resources in order to satisfy various demands in the study area and to minimise the risk of land salinisation.

2. THE STUDY AREA

The study area includes the JWPID, Lake Cowal and Bland Creek area (Figure 1). Established in 1944, the irrigation district has a total area of 93,123 ha. About 25% of this is capable of being irrigated. Water for the irrigation is diverted from the Lachlan River at Jemalong Weir and fed by gravity through some 306 km of unlined supply and drainage channels. Lake Cowal, which supports grazing and minor cropping activities when dry, is an ephemeral lake (8 km x 15 km in area) and is primarily fed by flood water from the Lachlan River and drainage from the Bland Creek.

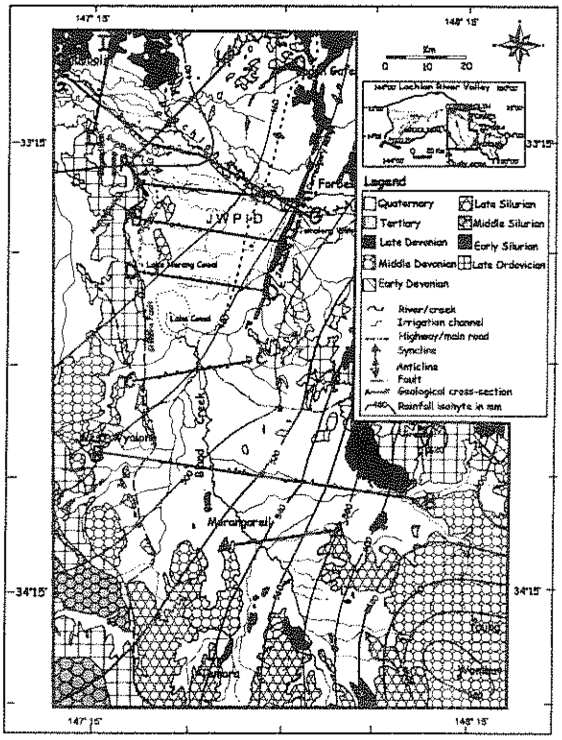

Figure 1. Geological map of the study area, locations of geological cross-sections and rainfall isohytes.

3. CLIMATE

Annual rainfall distribution in the study area decreases from east to west, ranging from 698 mm in Wombat to about 434 mm in Warroo (Figure 1). Monthly rainfall is almost uniformly distributed throughout the year, with relatively higher mean monthly rainfalls occurring during October and January. An approximately 50 years 'flip-flop' cyclical pattern of annual rainfall variation has recurred in the study area since the last century. The most widespread changes occurred around 1945-1946. This change is consistent with the changes in the catchment and over much of the south eastern Australia. The average maximum (January) and minimum (July) temperatures are about 32.1°C and 2°C, respectively. The average annual potential evapotranspiration from 1995 to 1997 at the irrigation district is about 1,387 mm, which is three times higher than the average annual rainfall.

4. HYDROLOGY

4.1 Runoff

In general, runoff at JWPID drains in westerly or south westerly directions towards Lake Cowal, Lake Nerang Cowal, Manna Creek and Bogandillon Creek. Flood runoff from the Lachlan River provides a major groundwater recharge for the district and surface water source for Lake Cowal. The flood water flows south-west along the floodway from the flood breakouts on the Lachlan River, through the JWPID. When Lake Cowal is full, floodwater begins to fill the adjoining Lake Nerang Cowal and will eventually overflow to the Lachlan River through the Manna and Bogandillon Creeks. Runoff from Bland Creek and its tributaries also flows into Lake Cowal. Lake Cowal has a storage capacity of 194,000 ML when full [Department of Water Resources, 1992] and frequency of partial inundation is approximately 50% (31 out of 64 years from 1930 to 1994).

4.2 Streamflow characteristics

The average (1941 to 1995) annual streamflow of the Lachlan River near Jemalong Weir is about 1,204,000 ML. In general, streamflows are high at this station during winter months and low during summer. The average monthly streamflow in August is the highest (228,000 ML), whereas January has the lowest streamflow (53,000 ML). Streamflow at this station is continuous due to water release from the headwater reservoir. Diversion of streamflow for irrigation at the Jemalong Weir was about 70,000 ML yr^{-1} from 1986/1987 to 1996/1997.

The Manna Creek has an annual streamflow of about 76,000 ML since 1975. Monthly streamflow is high from July to September, but very little water flows during summer months. In Bland Creek at Morangarell (Figure 1), the average annual streamflow recorded since 1977 is about 50,000 ML. Monthly streamflow distribution is quite similar to the other stations with high flows occurring in winter and low flows during summer. In Bogandillon Creek, streamflow is very low. Average annual streamflow in 1994 and 1995 at this station was 780 ML.

4.3 Surface water salinity

Between 1970 to 1981, the measured EC at the Jemalong Weir ranged from 210 to 640 $\mu S\ cm^{-1}$ with a median value of 350 $\mu S\ cm^{-1}$ [Kelly, 1988]. Using the average annual diversion of the irrigation water of about 70,000 ML and assuming a mean daily EC of 400 $\mu S\ cm^{-1}$, and a conversion factor of 0.64 it is estimated that the average daily salt load into the irrigation district is about 49 t d^{-1}.

In Bogandillon Creek, an EC value of 39,000 $\mu S\ cm^{-1}$ has been recorded in October 1994 at Birrack Bridge. In fact, at this section, about 34% of the recorded data are highly saline (above 15,000 $\mu S\ cm^{-1}$) and 52% fall into the brackish to saline category (1,500-15,000 $\mu S\ cm^{-1}$). The remaining 14% have an EC of less than 1,500 $\mu S\ cm^{-1}$. Meanwhile, water in Lake Cowal is fresh (less than 1,500 $\mu S\ cm^{-1}$). Its highest recorded EC is only about 6,000 µS cm^{-1} and was measured in February 1988 at the end of a dry period.

5. GEOLOGY

Figure 1 shows the geology of the study area and indicates that a large proportion of the area is covered by unconsolidated (Tertiary and Quaternary) sediments. The stratigraphic units in the study area include: Ordovician (tuff, phyllite, schist, sandstone, latite, siltstone, limestone, andesitic volcanics, basalt, and numerous igneous intrusions); Silurian (granite, sandstone, shale, slate, phyllite, conglomerate, acid lava and limestone); Devonian (massive sandstone, conglomerate, siltstone, granite, granodiorite, andesite, rhyolite, tuff, limestone and shale); Tertiary (basalt, laterite, conglomerate) and Quaternary (gravel, silt and clay).

Two distinct groups of unconsolidated sediments infill the paleochannels and floodplain of the study area, namely Lachlan and Cowra Formations [Williamson, 1986]. The Lachlan Formation is the older and deeper unit consisting of clays, silts, sands and gravels in varying admixtures. This formation is confined in the paleochannels and is believed to be of Pliocene age. The Cowra Formation, deposited since the Pleistocene, overlies unconformably the Lachlan Formation and basement rocks. It consists of moderately well sorted sand and gravel with interbedded clays. To investigate the subsurface geology of the study area, 9 cross-sections have been prepared. Locations of these cross-sections (A-A' to I-I') are shown on Figure 1, while Figures 2 and 3 show profiles of the selected cross-sections (A-A' and F-F'). In general, the density of the sand and gravel lenses increases from the southern part of the Bland Creek sub-catchment towards the Lachlan River.

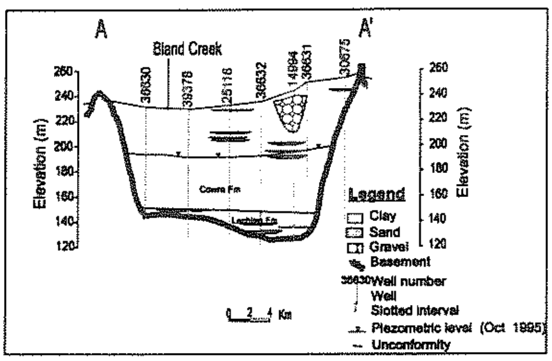

Figure 2. Geological cross-section A-A'.

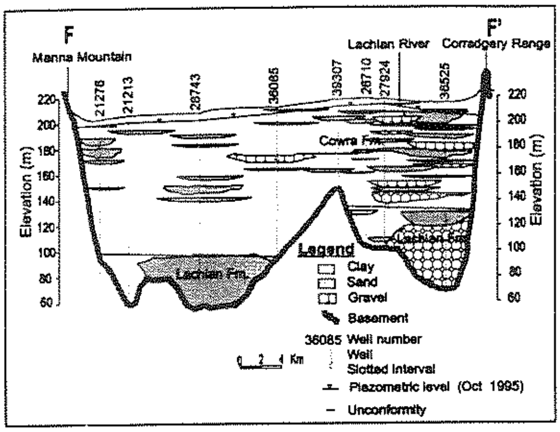

Figure 3. Geological cross-section F-F'.

6. HYDROGEOLOGY

Groundwater in the study area occurs in the unconsolidated sediments and in the fractured rocks. However, groundwater yields from fractured rocks are generally less than 1 litre per second. Unconsolidated sediments form the main aquifer consisting of Lachlan and Cowra Formations. In hydrogeological terms, these two formations act in combination as a watertable aquifer. However, on a local scale, individual sand and gravel lenses display their own characteristics and behaviour (as local confined or semi-confined aquifers).

6.1 Groundwater monitoring system

Groundwater level monitoring in the irrigation district started in 1944 at a limited number of sites. However, more monitoring wells were installed in 1968 to examine the watertable movements and groundwater quality of the entire irrigation district [Kelly, 1988]. More than 100 single or nested observation wells have been installed in the irrigation district since 1968. Around Lake Cowal, about 20 observation wells have been installed since 1994 to monitor groundwater level and electrical conductivity. Observation wells were also installed by North Mining Limited around the proposed Lake Cowal Gold Mine in 1994. Aside from the intensive groundwater level monitoring in the irrigation district, the Department of Land and Water Conservation has maintained regional observation bores at 75 sites in the study area.

6.2 Watertable rise

The watertable in the irrigation district has been rising since 1944. Table 1 shows that the watertable has risen by more than 8 m over the period of 1944 to 1992. A number of remarks regarding the estimates shown in Table 1 are as follows:

- The estimated watertable rise over the period of 1944-1968 is higher than the estimate (4 m) provided by Kelly [1988] over the same period. Unfortunately data were not available to us to verify these estimates.
- The low estimate of watertable rise over the period of 1969-1988 is due to a major gap (more than 7 years) in the data.
- William's [1993] estimate of watertable rise over the period of 1969-1992 is consistent with our estimate over the same period.

Table 1: Estimated watertable rise in the JWPID from 1944 to 1992.

Period	No. of years	Watertable rise in:	
		m	mm yr^{-1}
1944-1968	24	6	250
1969-1983	14	0.07	5
1983-1988	5	0.8	160
1988-1992	4	1.5	375
Total	47	8.37	178

Source of data: Williams [1993].

6.3 Watertable aquifer

Lachlan River has a dominant influence on the elevation of watertable aquifer in the irrigation district along its course in a northwesterly direction from the Jemalong Gap (Figure 4). The River and off-take canals are recharging the aquifer in the upstream areas as indicated by convex contours in the vicinity of the river course. Further downstream, the shape of the contours indicates that groundwater discharges into the river. Within the irrigation district, the response of the aquifer to the river stage declines with the distance away from the river. The watertable near the river responds to long duration high river stage with a time lag of about 2 months (Figure 5). Also evident is a dominant groundwater mound which coincides with the position of the Warroo Channel and is generating a significant component of groundwater flow to the west and southwest. This confirms Anderson et. al.'s [1993] finding that the mound has been developed by channel seepage over the years. The most significant feature of Figure 4 is the groundwater movement towards Lake Cowal. It is believed that in the past, groundwater from the Bland Creek sub-catchment had a natural gradient towards the Lachlan River [Anderson et. al., 1993]. It appears that the direction of the groundwater flow has been reversed and that the Bland Creek sub-catchment has a much lower contribution to the groundwater system of the JWPID. Figure 6 shows the depth of the watertable in January 1995 depicting a large area in the JWPID with watertable of 2 m below the ground surface. These areas with shallow watertable coincide with salt-affected areas.

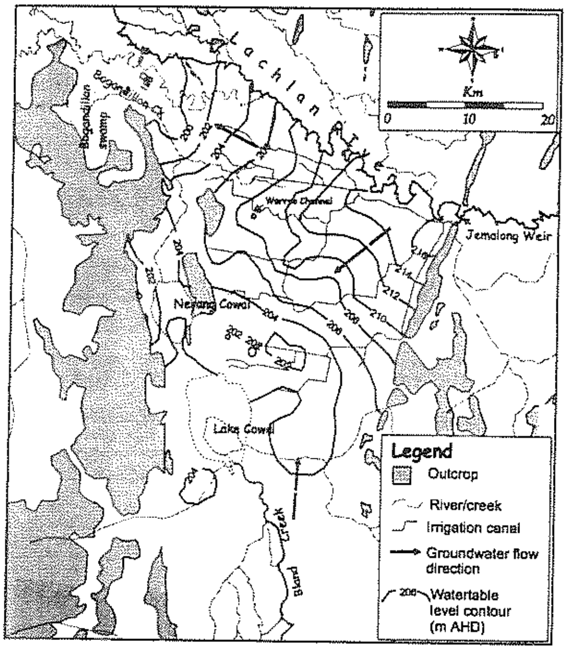

Figure 4. Watertable elevation map of the JWPID in January 1995.

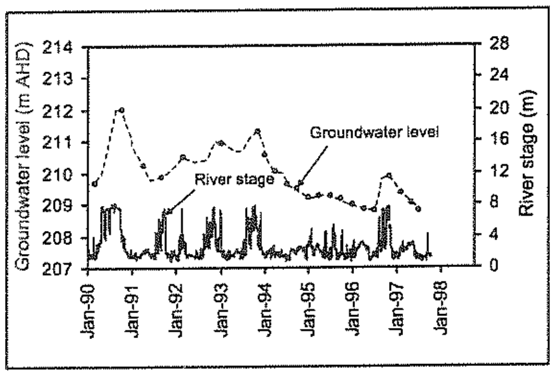

Figure 5. Lachlan River stage and watertable aquifer fluctuation.

6.4 Groundwater in sand and gravel lenses

Piezometric analysis of the groundwater system within the sand and gravel lenses is complex because of their structure and irregular distribution. Piezometric heads appear to be influenced by the thickness of the individual lenses, and the hydraulic properties of the clay layers that separate the lenses. Because the lenses are discontinuous, it is not appropriate to prepare a piezometric map using data from individual lenses.

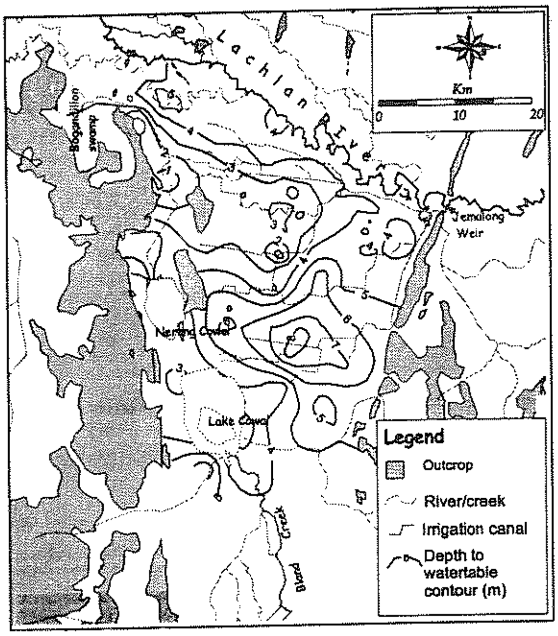

Figure 6. Watertable depth map of the JWPID in January 1995.

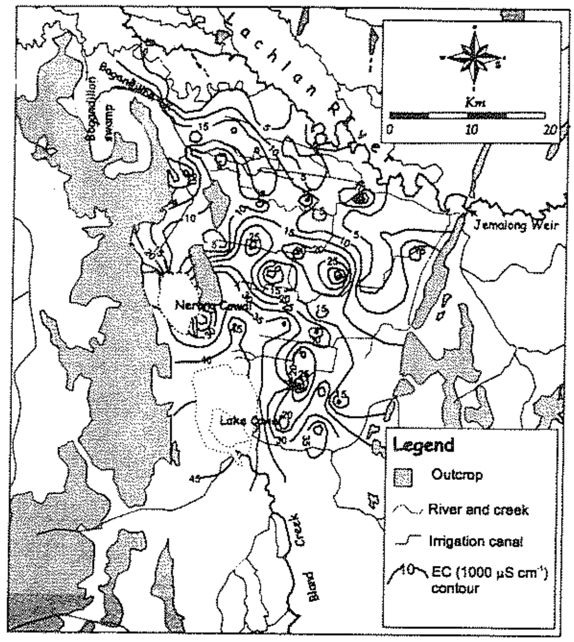

Figure 7. Groundwater electrical conductivity map of the JWPID in January 1997.

6.5 Hydrodynamic parameters

Pumping tests carried out in the JWPID indicate that transmissivity values range from 60 to 300 $m^2 d^{-1}$. Storativity at the JWPID also varies from site to site, ranging from 0.0025 to 0.004. It should be noted that the low values of storativity (which are not representative of a watertable aquifer) are due to the fact that pumping tests were undertaken in the sand lenses.

Several Department of Land and Water Conservation investigation bores around the study area have been pump tested. The estimated transmissivity values range from 113 to 780 $m^2 d^{-1}$ for the Cowra Formation and 587 to 1160 $m^2 d^{-1}$ for the Lachlan Formation, respectively. The computed hydraulic conductivity of the respective formations are of the same order of magnitude, from $0.8x10^{-3}$ to $2.7x10^{-3}$ m d^{-1} for the Cowra Formation and $1.7x10^{-3}$ to $4.5x10^{-3}$ m d^{-1} for the Lachlan Formation.

6.6 Salinity of the watertable aquifer

About 120 shallow observation wells (4-20 m deep) have EC records since 1968, with an additional 19 and 22 observation wells in 1983 and 1994, respectively. EC values near the Lachlan River are relatively low (Figure 7). A large area of very high groundwater salinity occurs in the south-west around Lakes Cowal and Nerang Cowal. In fact, some observation wells have EC values of over 40,000 µS cm^{-1}.

6.7 Salinity of the sand and gravel lenses

Electrical conductivity measurements at the regional groundwater bores were taken mostly during the time when groundwater investigation commenced in 1968. Although the historical data for these groundwater bores are very limited (only three measurements of EC have been taken since 1968), EC values clearly vary with depth. Figure 8 shows an example of EC variation with depth in one of the regional observation bores (Bore 36551) located in the irrigation district. In general, EC is lower in lenses deeper than 40-50 m with a range of 190 to 48,700 µS cm^{-1} and an average of 3,700 µS cm^{-1}. In the shallower lenses, EC ranges from 195 to 60,000 µS cm^{-1} and averages 5,700 µS cm^{-1}. However, there are some sites where the EC of the deeper lenses is higher than that in the shallower lenses.

In the Lake Cowal area, EC is in the range of 32,400 to 72,000 µS cm^{-1} ,which is significantly more saline than the Lake water itself. However, the Lake sits on a 7 to 10 m thick laterally continuous clay layer with very low vertical hydraulic conductivity (0.00077 to 0.000027 m d^{-1}) which protects the lake from the underlying saline aquifer.

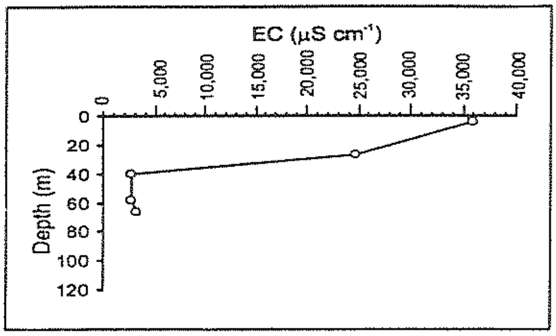

Figure 8. Variations of EC values with depth in Bore 36551 (Longitude 147^0 29', Latitude 33^0 26').

7. MODEL DEVELOPMENT

A three-dimensional groundwater flow model covering the unconsolidated sediments of the JWPID and Lake Cowal area is being developed using MODFLOW. The modelled area extends from the Lachlan River in the north to Lake Cowal in the south. The main objectives of this model are to: quantify various components of groundwater balance; assess the relative importance of salinisation processess; and to develop the best management strategies for conjunctive use of surface and groundwater resources in order to satisfy various demands in the study area and to minimise the risk of land salinisation.

MODFLOW is a U.S. Geological Survey modular and finite-difference groundwater model which simulates flow in three dimensions (MacDonald and Harbaugh, 1984). It provides solution of the three dimensional partial difference equation of groundwater flow in an aquifer subject to recharge and pumping.

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right)= S_s(x,y,z)\frac{\partial h}{\partial t}+Q(x,y,z,t)$$

Here the hydraulic conductivity K and storativity S_s represent physical aquifer properties in space, h is the hydraulic head, Q is the source/sink term, (x,y,z) *is* a cartesian coordinate system and t is time. Together with MODPATH and MT3D, MODFLOW has been integrated in Visual MODFLOW to provide an easy-to-use graphical modelling environment for three dimensional groundwater flow and contaminant transport simulations.

It should be noted that groundwater models are traditionally calibrated via a tedious and frustrating trial and error method. In this research, attempts will be made to explore the possibility of using PEST software as an alternative. PEST (which is an acronym for Parameter ESTimation) is a model-independent and non-linear parameter estimator which facilitates the task of model calibration (Watermark Computing, 1994). PEST adjusts the model parameters until the fit between the model output and observed values is optimised in the weighted least squares sense.

8. ACKNOWLEDGMENTS

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