Groundwater Modelling of an Irrigated Area of the Lachlan Catchment for Salinity Management

R.M. Lampayan[a], **F. Ghassemi**[b] **and I. White**[b]

[a]*The International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines (RLampayan@CGIAR.ORG)*
[b]*Centre for Resource and Environmental Studies, The Australian National University, Canberra ACT 0200, Australia*

Abstract: The Jemalong and Wyldes Plains Irrigation District (JWPID) in the Lachlan Catchment (New South Wales, Australia) is threatened with rising watertable and salinisation of its western part. A numerical three-dimensional groundwater flow model was developed for the area using Visual MODFLOW. The modelled domain extends approximately 45 km from east to west and 66 km from north to south and covers an area of about 170,000 ha. The aquifer system was discretised horizontally by a uniform grid of 500 m x 500 m. Vertically, the aquifer system has been discretised to represent 4 layers of the aquifer system. The model was successfully calibrated in steady-state for April 1988 and under transient conditions for the period May 1988 to July 1997. The model revealed significant basement leakage through apparent faults and major floods dominate regional groundwater rises. The calibrated model was used to simulate a number of management options to evaluate their impact on the groundwater system in the study area. These include '*no change*', reduce recharge through channel sealing and drainage efficiency and tree-planting options. The simulations indicate that by sealing channels and planting trees in strategic areas, it is possible to control watertable rise and expansion of land salinisation under average conditions.

Keywords: Salinisation; Groundwater; Modelling; Tree-planting

1. INTRODUCTION

A wide range of management options is available to control salinity on irrigated and dryland agricultural areas and watercourses. Salinity management options maybe broadly classified as engineering, biological and policy options [Ghassemi et al., 1995]. However, choices of options depend on particular circumstances. Technical, economic, social and political considerations are the major influences on the implementation of these options.

The Jemalong and Wyldes Plains Irrigation District (JWPID) near the Lachlan River, NSW, faces rising groundwater levels and increasing salinisation. Not all salinity control options are applicable there. Improvement of irrigation and drainage efficiency and strategic tree-planting appear to be the feasible options. In this paper, these options are examined using the calibrated three-dimensional groundwater model employing Visual MODFLOW [Waterloo Hydrogeologic Inc, 2000] developed for the area.

2. THE STUDY AREA

The study area includes the JWPID and Lake Cowal (Figure 1). The irrigation district, established in 1944, has a total area of 93,000 ha with water for irrigation diverted from the Lachlan River at the Jemalong Weir. The average annual irrigation delivery for the whole irrigation system is about 70 x 10^6 m^3. In any one year, the irrigated area ranges from 12,000 to 20,000 ha. Annual pasture, lucerne and winter cereals are widely grown and up to 1000 ha of rice.

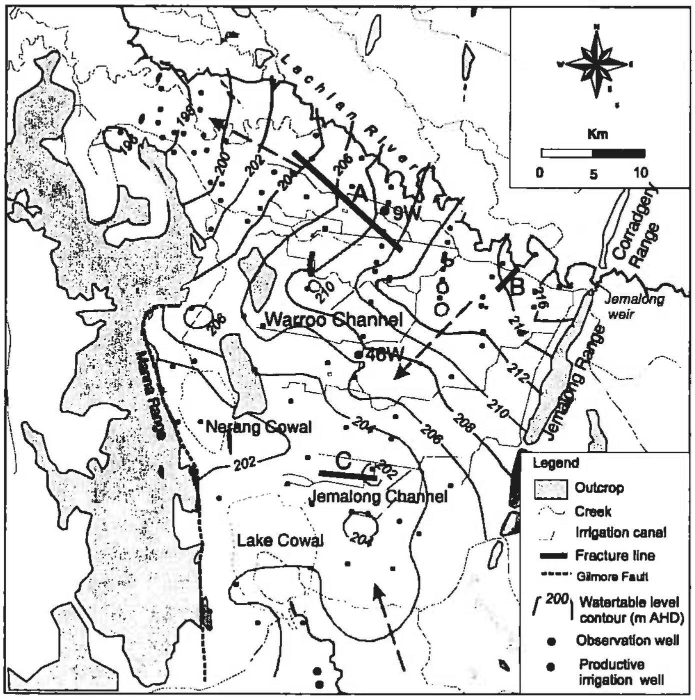

Figure 1. Groundwater heads in 1997.

Mean annual rainfall in the study area decreases from 500 mm in the east to about 440 mm to the west. Average daily potential evaportranspiration (ET) during summer months is about 6.6 mm d^{-1}, and about 1.3 mm d^{-1} during winter months.

3. HYDROGEOLOGY

Two different groups of unconsolidated sediments infill the paleochannels and floodplain. The Lachlan Formation is the older and deeper unit consisting of clays, silts, sands and gravels in varying admixtures. This formation is confined to the paleochannels and is believed to be of Pliocene age. The Cowra Formation, deposited since the Pleistocene, unconformably overlies the Lachlan Formation. It consists of moderately well sorted sands and gravels with inter-bedded clays. The basement rocks are fractured and have the potential of draining the aquifer system.

Shallow observation wells used in this analysis (Figure 1) were drilled from 1968 to 1994 to examine watertable dynamics and groundwater quality in the irrigation district. The analysis indicated an average groundwater rise of 2.6 m between March 1969 and October 1990. A major flood in 1990 caused the watertable in the irrigation district to rise close to the ground surface and in almost half of the JWPID, the watertable was less than 2 m below the surface. After this flood, regional groundwater levels gradually declined by about 2 m between October 1990 and July 1997. However, near Lake Cowal, the watertable has continued to rise, even during non-flood periods. Periodic, major floods have a clear and enormous influence on regional watertable heights.

The Lachlan River along its course from Jemalong Gap has a dominant influence on the groundwater in the irrigation district(Figure 1). The river recharges the aquifer in the upstream areas, while further downstream, groundwater discharges to the river. The groundwater flow regime in the irrigation district is the result of two flow systems, one from the Lachlan River and the other from Bland Creek towards Lake Cowal. The dominant flow is that from the Lachlan River.

Recharge areas are located close to the Jemalong Gap and along the Lachlan River, while discharge areas are on the western side of the District.

The Gilmore Fault (Figure 1) which lies along the edges of the Manna Range has been believed to be a conduit for groundwater drainage in the area [Coffey Partners International Pty Ltd, 1994].

Groundwater salinity in a large part of the study area is already high (5,000 to 40,000 $\mu S\ cm^{-1}$). A large area of highly saline groundwater occurs in the south-west around Lakes Cowal and Nerang Cowal. However, Lake Cowal's surface water is relatively fresh. This is because the lake lies on a 7 to 10 m of thick laterally continuous clay with very low vertical hydraulic conductivity which so far has protected the lake from the underlying saline aquifer.

4. GROUNDWATER MODEL AND CALIBRATION

The aquifer system in the study area was dicretised in the horizontal into 123 rows and 84 columns to form cells of equal sizes of 500 m x 500 m dimensions (Figure 2). In the vertical (Figure 3), the aquifer was discretised into four layers representing the main aquifers and aquitards.

Boundary conditions adopted for the groundwater modelling are no-flow boundaries at the eastern and western limits where the Ranges provide natural barriers for the groundwater flow. The northern limit of the modelled area coinciding with the Lachlan River is treated as constant head boundary for each cell. The southern boundary is a flow boundary where groundwater flow from the Bland Creek catchment enters the modelled area (Figure 2). A flow boundary condition was also assigned to the 5 km section at the northwestern limit of the modelled area in keeping with the head distribution in this region (Figure 1).

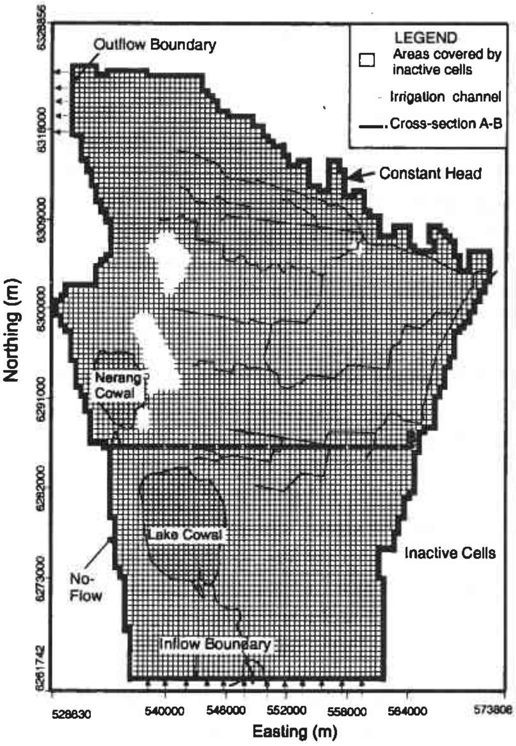

Figure 2. Horizontal discretisation of the aquifers.

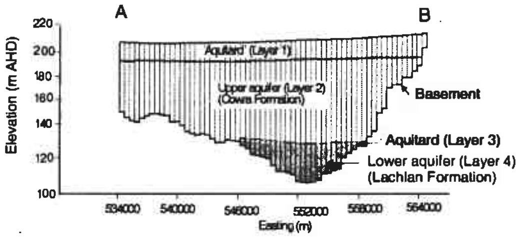

Figure 3. Vertical discretisation of the aquifers.

The model was calibrated in steady-state for April 1988. This period was selected because groundwater level observations before 1988 were very limited. The initial boundary conditions, hydraulic conductivities, recharge rates and possible leakages were taken from measured values. Measured monthly rainfall was used as an input, ET was estimated from watertable depth and measured pan evaporation was multiplied by an appropriate monthly pan coefficient to estimate potential evaporation. The ET function used assumed that ET equaled the estimated potential rate when the water table was at the soil surface and was zero when the watertable depth exceeded the extinction depth of 2.5 m in irrigated areas and 2 m in non-irrigated areas. Between these two limits, ET varied linearly.

Other parameters were estimated from data obtained from the Department of Land and Water Conservation and from previous studies in the modelled area. Model parameters were adjusted until the best fit between the computed and observed heads was reached. Then the steady-state calibrated hydraulic heads were used as the initial condition for transient calibration of the model from May 1988 to July 1997 using a monthly timestep.

Figures 4 and 5 show the match between the measured and computed piezometric heads for two observation wells in the transient calibration simulation. The match between the piezometric head contours interpolated from computed and measured heads for July 1997 is shown in Figure 6, depicting the final timestep (timestep 111) of the calibrated model.

Mean annual volume of various components of the groundwater balance were estimated from the calibrated transient flow simulations (Table 1). Rainfall is the major source of recharge for the aquifer system in non-flood periods. Seepage from the Warroo channel also provides a significant contribution to the recharge in the system. A major source of groundwater loss is through direct evapotranspiration of the shallow groundwater. The model showed that in order to fit the observed head distribution, leakage from the basement at three locations (fracture lines A, B and C in Figure 1) had to be assumed.

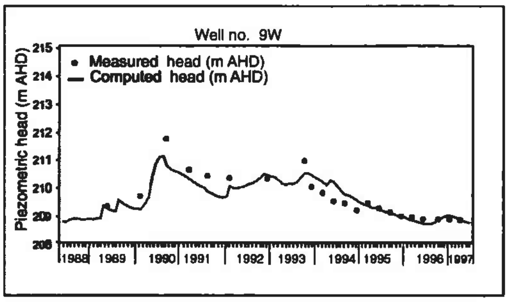

Figure 4. Measured and computed heads in transient simulation at observation well 9W.

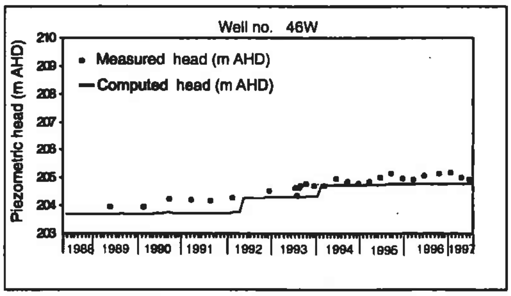

Figure 5. Measured and computed heads in transient simulation at observation well 46W.

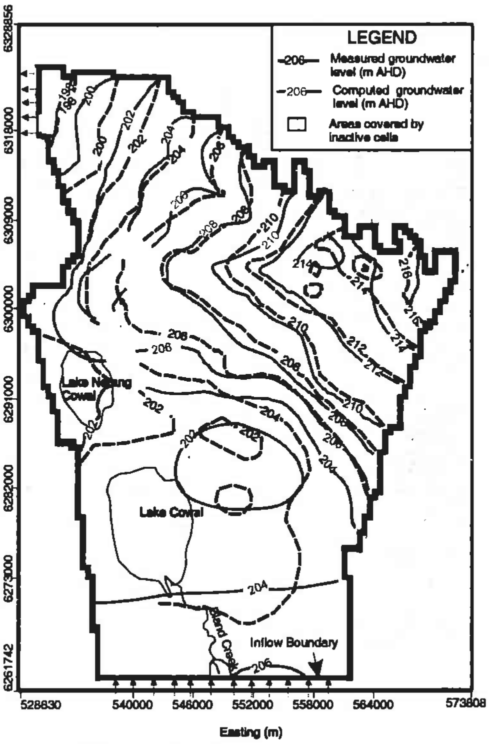

Figure 6. Measured and computed piezometric heads in transient simulation for July 1997.

5. SIMULATION OF MANAGEMENT OPTIONS

The following management options have been simulated to assess the behaviour of the aquifer system: (a) *'no change'* option; (b) sealing the Warroo channel; and (c) partial area tree-planting. These three options were simulated over a 23-year period from 1998 to 2020.

5.1 *'No change'* option

The *'no change'* option assumes that general land use practices remain unaltered until 2020. In this approach, input time-dependent parameters such as recharge, constant head boundary, inflow and outflow boundaries, drainage and leakages were assumed to be constant at their mean values over the simulation period. Inputs were prepared as annual values to run the model in annual timesteps using the calibrated July 1997 piezometric heads as the initial condition. With annual timesteps, 23 timesteps were required to complete the simulation.

Table 1 compares the mean annual groundwater balance for the period 1998 to 2020 under the *'no change'* option with the corresponding values for the year 2020 and with the transient calibration period. Except for recharge and ET, mean annual volumes of groundwater components between *'no change'* option and transient calibration are comparable. The large difference in the computed values of recharge is due to the fact that the transient calibration period from May 1988 to 1997 had a series of floods and high rainfalls, while the mean recharge values used in the *'no change'* option is lower and constant for the entire simulation period. With lower constant recharge, groundwater levels are lower and both direct groundwater evapotranspiration and the amount of drainage along the Gilmore Fault at the western side of the modelled area are significantly smaller under the *'no change'*option.

The resulting mean annual inflows and outflows under the *'no change'* option are about half of the mean inflows and outflows for the transient calibration. On the other hand, under *'no change'* option the total input in year 2020 is slightly lower than the average total input over the forecasting period. Under the same option, total output in year 2020 is slightly larger than the average total outflow for1998 to 2020.

Table 1. Comparison of annual groundwater balance for the transient calibration, and *'no change'* option.

Components	Annual volume (10^3 m^3)		
	Calibra-tion*	*'No change'* option (av 1998-2020)	*'No change'* option (2020)
Input			
Constant head	4216	3516.3	3478.4
Recharge	13630.5	5021.7	5021.7
Inflow boundary	334.0	334.0	326.4
Total input	**18180.5**	**8872.0**	**8826.5**
Output			
Constant head	2963.0	1324.1	1354.4
Outflowboundary	10.2	10.2	10.2
Leakage:			
Fracture A	2154.6	2154.6	2154.6
Fracture B	438.2	438.2	438.2
Fracture C	184.7	184.7	184.7
Total	2777.5	2777.5	2777.5
ET	11056	4222.7	4224.5
Drainage	339.6	229.6	216.8
Total output	**17146.3**	**8564.1**	**8583.4**
Total input-output	*1034.2*	*307.9*	*243.1*
Change in storage	*1034.1*	*307.1*	*243.0*
Balance error	*0.1*	*0.8*	*0.1*

*Results of transient calibration.

5.2 Sealing the Warroo Channel

The transient calibration showed that about 2.1 x 10^6 m^3 per year of groundwater recharge comes from seepage losses of irrigation water in the Warroo Channel. These losses account for approximately 5% of the total delivered irrigation water in the Warroo Channel and about 2.5% of the total delivery for the entire irrigation district. The area is also subjected to flooding. Therefore, one feasible option is sealing the Warroo Channel by canal lining and reducing the longevity of flooding events by improving drainage.

Simulation of channel sealing showed a decline of watertable depths of over 1 m (Figure 7) for the Warroo Channel area compared to the *'no change'* option in 2020. The mean annual recharge rate of the modelled area was reduced by about 38% as a result of eliminating seepage losses from the Warroo Channel.

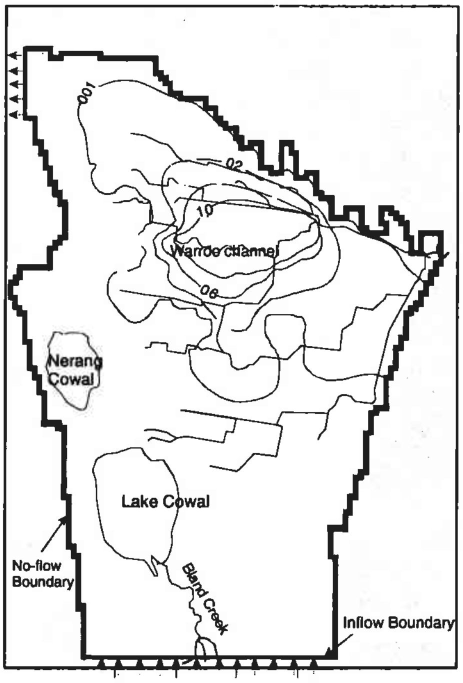

Figure 7. Decline in watertable depth for year 2020 due to sealing of Warroo Channel as compared with the 'no change' option.

5.3 Tree-planting Strategy

In the JWPID, groundwater pumping with the objective of lowering groundwater levels could not be considered because no option is available for the disposal of pumped saline groundwater. Tree-planting provides a better option.

Reforestation and farm tree establishment are major control measures in salinity management plans for the Australian catchments, based on an expectation that ET from forests or woodlands will be greater than crops and pastures in the same location [Clifton et al., 1993]. One of the reforestation strategies that has recently received increased attention in Australia is alley farming. Alley farming is a technique in which crops and pastures are grown between parallel belts of trees [Lefroy and Scott, 1994].

A density of 80 trees per ha (20% plantation) was assumed to be reasonable for alley farming in an area with an average annual rainfall of 434 mm. Trees are assumed to extract groundwater to depths of 4 m to 8 m from the ground surface. However, extraction rates vary according to age of the tree.

Due to the plateauing of canopy diameter, leaf area and tree height after five years [Schofield, 1984], it was assumed that tree water use would reach a maximum after six years. Thereafter, water use remains constant. Based on reported water use by Morris and Collopy [1999] and others, the annual average rate of groundwater extraction by a single tree from one year up to six years after planting used in simulations are shown in Table 2. From these values, the computed groundwater extraction rates by trees for each 500 m x 500 m model cell (about 2000 trees) under alley farming scheme ranges from 4 m^3 d^{-1} to 36 m^3 d^{-1} from the first to the sixth year. After the sixth year, groundwater extraction rate remains constant. Here, *E. camaldulensis* has been assumed as the tree species for tree-planting strategy because this species can tolerate high levels of groundwater salinity in the range of 4,000 – 5,000 µS cm^{-1} [Thomson et al., 1987].

Table 2. Assumed rate of groundwater extraction per tree from 1 to 6 years after planting for *E. camaldulensis* [Morris and Collopy, 1999].

Years after planting	Extraction rate (L $tree^{-1}$ d^{-1})
1	2
2	5
3	10
4	12
5	14
6	18

Two options were simulated under the tree-planting strategy. The first option was alley farming on the north-western part of the irrigation district (designated as Area A in Figure 8). As groundwater flows towards the salt-affected area, tree plantings in this area are aimed to partially intercept this flow and thus lowering the watertable.

The second option was alley farming in the southern part of the study area. The aim of this option is to examine the impacts of tree planting on the continually rising watertable in the Lake Cowal area which in long term will cause severe land salinisation as well as increasing the salinity of the Lake Cowal's water. Under this option, three designated areas (B1, B2 and B3 in Figure 9) are assumed to be under alley farming.

5.3.1 Tree plantation in Area A

A series of model runs was undertaken to identify the optimal extent of the area for tree-planting. The assumed extent of the area for alley farming is about 10.5 km x 1 km (1,050 ha), comprising of about 42 model cells.

Under this option, there is a significant reduction in watertable depth of order 0.5 to 2 m in year 2020 over the plantation area (Figure 8). The simulations of alley farming options in this area indicate the potential of this strategy for halting land salinisation. Obviously, extending the area of alley farming to the west of the simulated area will increase the effectiveness of this option.

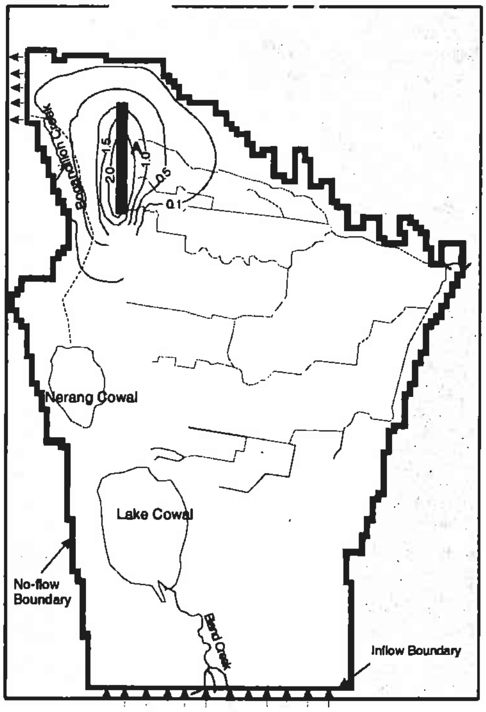

Figure 8. Decline in watertable depths (m) in year 2020 due to tree-planting strategy (Area A), as compared with the '*no change*' scenario.

5.3.2 Tree-planting in Areas B1, B2 and B3

The groundwater level in the southern part of the study area continues to rise even during non-flood periods. This could become critical in the future when the saline watertable comes closer to the land surface causing land salinisation and a possible increase salinity in the Lake Cowal. Tree plantation provides a good management option to halt these processes.

The optimal size of plantations at each designated plantation areas under this option was estimated through series of model runs. Initially, a single plantation area (B1) was selected parallel to the Jemalong Channel to intercept the groundwater flow from the irrigation district towards the south.

However, a single plantation area was insufficient to lower the watertable. As a result, two additional plantation areas (B2 and B3) were added to effectively lower the watertable. The approximated plantation size at area B1 is 15.5 km x 1 km (1,550 ha), while B2 and B3 are 9.5 km x 0.5 km (475 ha) and 14 km x 1 km (1,400 ha), respectively.

The simulations show a significant decline in watertable depths of over 4 m in some areas in year 2020. A large portion of the area has a simulated watertable decline of about 1 m (Figure 9). The decline in groundwater level under this option for observation well 5n (Figure 10) showed that for the first few years of plantation, groundwater continued to rise. When trees become relatively mature, predicted groundwater levels started to decline.

6. SUMMARY AND CONCLUSIONS

Groundwater analysis and modelling in the Jemalong and Wyldes Plains Irrigation District has provided a better understanding of the shallow aquifer's behaviour and its interactions with irrigation and surface water resources. Periodic floods dominate groundwater levels in the region, however persistent groundwater rises occur in the Lake Cowal region. Management options for the region were simulated using a calibrated three-dimensional groundwater model. The model predicted that sealing of the Warroo channel would lower the local watertable by more than 1 m in the long term. Alley tree planting of 20 percent to partially intercept groundwater flow towards the northeast area is predicted to lower the watertable by over 0.5 m in the salt affected areas. Finally, on the southern part of the study area where a continuous watertable rise has been observed around Lake Cowal, simulation indicated that modest tree planting in three locations would lower watertable depths by 1 m. It is concluded that channel sealing and partial tree plantation in a small portions can reverse the current trend in watertable rise and the associated land salinisation in the long term.

Finally, considering the significant impact of the fractured basement rocks on the water balance of the aquifer system, it is recommended that field investigations be undertaken to identify their nature, extent and hydraulic characteristics.

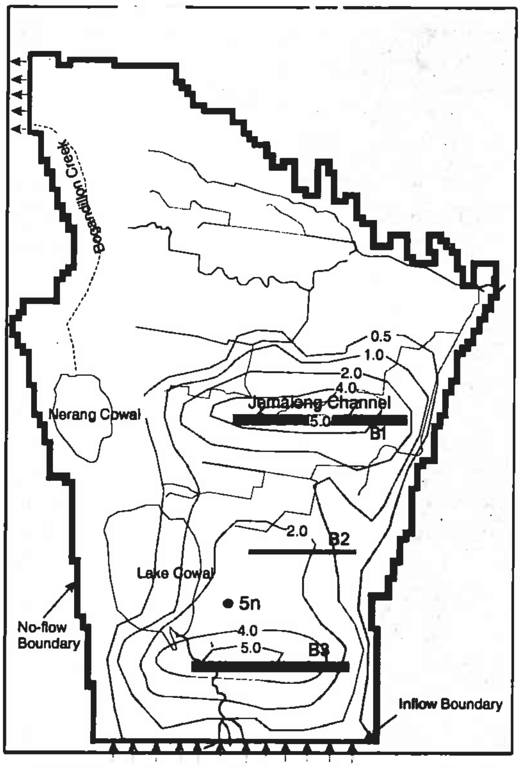

Figure 9. Decline in watertable depths (m) in year 2020 due to tree-planting strategy in the southern part of the study area as compared with *'no change'* scenario.

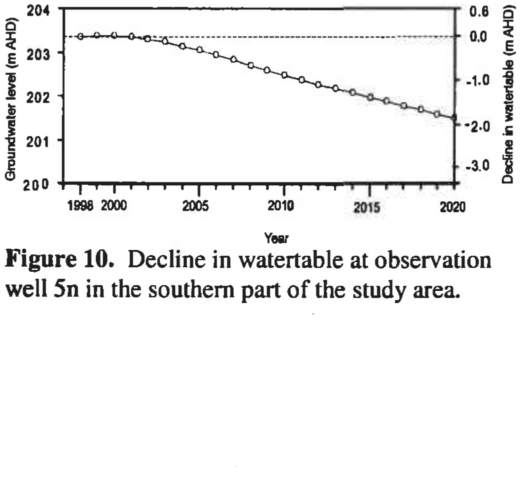

Figure 10. Decline in watertable at observation well 5n in the southern part of the study area.

7. REFERENCES

Clifton, C.A., P. Miles, W. Harvey, B. Trebilcock, and J. Morris, Evaluation of the growing strategies for reducing groundwater recharge in the Hill Country of Northern Victoria, paper presented to the National Conference on Land Management for Dryland Salinity Control, La Trobe University, Bendigo, Victoria, Sept, 1993.

Coffey Partners International Pty Ltd, Groundwater modelling study, Jemalong Wyldes Plains, Report number G375/2-AB, Department of Water Resources, New South Wales, 1994.

Ghassemi, F., A.J. Jakeman and H.A. Nix, *Salinisation of Land and Water Resources - Human Causes, Extent, Management and Case Studies*, UNSW Press Ltd, Sydney 2052 Australia, 526 p, 1995.

Lefroy, T. and P. Scott, Alley farming: new vision for Western Australian farmland. *Journal of Agriculture, Western Australia,* 35, 119-26, 1994.

Morris, J.D. and J.J. Collopy, Water use and salt accumulation by *E. Camaldulensis* and *Casuarina Cunninghamiana* on a site with shallow saline groundwater. *Agricultural Water Management*, 39, 205-227, 1999.

Schofield, N.J., A Simulation model predicting winter interception losses from reforestation stands in south-west, Western Australia, *Australian Forestry Research*, 14, 105-127, 1984.

Thomson, L.A.J., J.D. Morris, and G.M. Halloran, Salt tolerance in eucalypts, Proceedings Conference on Afforestation of Salt-affected Soils, Karnal, India, Feb. 1987.

Waterloo Hydrogeologic Inc., Visual MODFLOW user's manual, Waterloo Hydrogeologic Inc., Waterloo, Ontario, Canada, 2000.