Application Of 1-D And 3-D Models In A Regional Context

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EXTENDED ABSTRACT

Groundwater levels rose (an average of 10m) (mostly in 1970's and 80's) due to irrigation induced recharge to the groundwater in Coleambally Irrigation Area (CIA). Water table depth rise was a direct result of the net amount of recharge over and above the regional groundwater outflow capacity. Control of net recharge through a range of options is critical to the sustainability of CIA and requires both on-farm and regional management options for the groundwater discharge zones. There are two components to the management of recharge: The on-farm component, and the regional component. A regional groundwater model is used to look at overall targets of net recharge within the CIA. This model sets net recharge targets and is used to identify key processes and examine the effect of regional groundwater pumping on watertables and evaluate scenarios. The on-farm component captures the variability of soils, crops, and management at different parts of the region.

This study is aimed at investigating regional groundwater outflow characteristics in CIA on clustered farms basis to help identify Land and Water Management Plan (LWMP) targets for water use efficiency and drainage improvement at farm level linked to the regional targets. The groundwater balance for clusters of farms and the groundwater zones was obtained by calibrating a regional groundwater model (MODFLOW) for the Coleambally area. Calibration of the groundwater model helped to quantify vertical and lateral groundwater outflow capacity on a regional and sub-regional basis. Estimates of vertical recharge were obtained by using one-dimensional water balance model called APSIM. APSIM model was applied to 18 detailed monitoring piezometer sites with known water level records scattered in 5 zones of the CIA (Figure 1) to calculate the drainage values (mm/day) for each zone. APSIM results indicate risk of salinisation in most zones. APSIM results depict only the 1-D groundwater dynamics under non-irrigated areas whereas mixed landuse were represented in the MODFLOW cells. A possible way forward is to carry out APSIM simulations for all landuses in each land management unit. However it would require detailed data for each landuse and soil type which was beyond the scope of this study. Although APSIM fluxes do not directly match the MODFLOW calibrated values, they were useful in providing a cross check on the relative magnitude.

The analysis has shown that on a regional basis the vertical leakage capacity of the shallow aquifers (20,000-30,000 ML/year) needs to be matched with the overall recharge to maintain current groundwater levels. Since groundwater levels in some regions e.g. south and west (zones 3 and 4 in Figure 1) are already within the root zone there is a need to initially reduce groundwater recharge to less than the aquifer outflow capacity. These regions have the highest risk of soil salinisation. There is a need to reduce total on farm recharge to less than 0.5 ML/ha using winter cropping options as well as limited rice water use and improved water use efficiency. Drainage and reuse options should be considered for some parts of these zones.

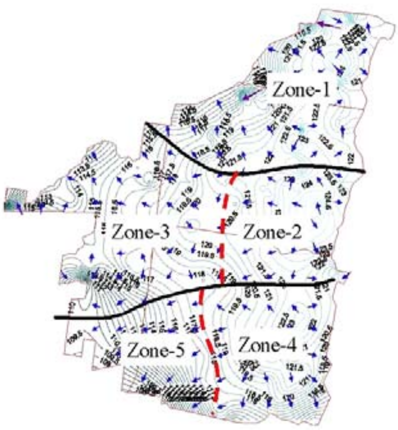

Figure 1. Groundwater zones in the Coleambally Irrigation Area

1. INTRODUCTION

The Coleambally Irrigation Area (CIA) is located in the eastern part of the Murray Basin, Australia. Prior to irrigation, watertable levels were at depths of 15-20 m. During the 1960's irrigation of 79,000 ha of land began in the CIA with irrigation water diverted from Gogeldrie Weir 25 km east of Darlington Point (Figure 2). Irrigation accessions to groundwater led to significant increases in the shallow watertable areas during the 1980's, and now a groundwater mound exists beneath the CIA. The Coleambally Irrigation Area (CIA) faces the problem of waterlogging and salinisation the same as other irrigation areas in semi arid regions. However, large scale degradation can be avoided, if the situation is closely monitored and action is taken when causative processes are identified.

The depth to the watertable is controlled by the amount of net recharge. Net recharge is defined as recharge minus discharge and leakage to the deep aquifer and is the amount of water that adds to the groundwater store. The control of net recharge through a range of options is critical to the productive sustainability of the CIA.

The total average rainfall in the CIA lies between 400 – 450 mm/year and the main crop type is rice, which is grown under flooded conditions. The shallow watertables fluctuates every year due to changes in climatic conditions and land management practices within the CIA.

The Coleambally irrigation overlies the lower Murrumbidgee alluvial aquifer system which starts downstream of Narrandera and consists of unconsolidated alluvial deposits of sands, silts, clays and peat. This alluvial system consist of three major aquifers i.e. the shallow Shepparton, intermediate Calivil and the deep Renmark Formations (Brown and Stephenson 1991). The Shepparton formation was deposited during the late tertiary to the quaternary period and mainly consists of unconsolidated to poorly consolidated, mottled, variegated clays and silty clays with lenses of polymictic, coarse to fine sand and gravel, partly modified by pedogenesis. The shallow Shepparton sediments were deposited by a series of prior streams over several million years. Below the Shepparton formation (20 to 60 meters thick), the Calivil aquifer systems often extends to depths greater than 150 meters. Water movement through the deep aquifers is generally from east to west except in the area with major groundwater pumping around Darlington Point. Recharge to the deep aquifers is mainly from the Murrumbidgee River downstream of Narrandera and from the irrigation areas (Figure 2).

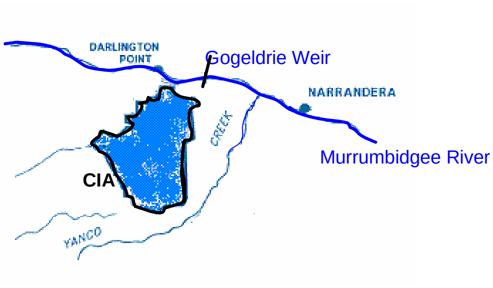

Figure 2. Location of the Coleambally Irrigation Area (CIA)

The salinity of the groundwater increases from east to west. The shallow Shepparton aquifer is often very saline especially under the irrigation areas where salinity levels can be high e.g. 20-30 dS/m.

This study was carried out to quantify vertical and lateral groundwater outflow capacity on a regional and sub-regional basis to help farmers and Coleambally Irrigation to achieve groundwater and salinity management targets.

2. METHODOLOGY

To assess various options available to farmers and Coleambally Irrigation to manage the watertable and thereby salinity within the CIA, a combination of modeling approaches was taken. Groundwater outflow rates for shallow aquifers on a farm cluster and zonal basis were calculated by using a numerical groundwater model of the region. Estimates of vertical recharge were obtained by using one-dimensional vertical modeling and cross-validated with the net recharge estimates from the calibrated groundwater model. Net recharge targets and groundwater management options on a zone by zone basis (Figure-1) were then determined by using groundwater balance for each zone.

2.1. 1-D Model

APSIM (Agricultural Production Systems Simulator) was used for the 1-D modelling. APSIM is a cropping system modelling environment specially designed to allow a plug-in-pull-out approach for the integration of various simulation models (Keating *et al.* 2003). It is a product of the Agricultural Production Systems Research Unit (APSRU) and can simulate daily soil water balance when climate and soil data are given. APSIM can be configured with modules suitable for the simulation of many different systems. SWIM module in APSIM (Verburg *et al.* 1996) provides a numerical simulation of movement and uptake of water based on Richards' equation. SWIM, with flexible time-varying boundary conditions, can simulate infiltration, soil moisture profile (one-dimensional), plant uptake, soil evaporation, deep drainage and leaching.

APSIM was applied to 18 piezometer sites with known water level records (six-hourly measurements) scattered in different zones of the CIA. Soil maps of the region were used to locate the sites. Hydraulic properties of soils (soil water characteristics and hydraulic conductivity curves) were estimated using typical values for physical properties of soil types giving upper & lower limits on soil moisture holding capacity. The two-point method (Cresswell and Paydar 1996) was then used for fitting smoothed Brooks - Corey equation to the soil water characteristic curves. For hydraulic conductivity function, Mualem model (1976) was used (HYPROPS in Verburg *et al.* 1996). Most sites were characterised as red-brown earth with a few on self-mulching clays.

No crop was simulated at the piezometer sites as they were not located on cropping sites. Given the watertable readings of the piezometers (converted to daily values) as the bottom boundary condition, the model simulated the daily water flow into and out of the profile (up to 7.5 m deep). Climate data was obtained from patched-point meteorological Data (Jeffery *et al.* 2001) for Jerilderie Station 74040 (-34.95, 145.72). The same climate data was used for all sites. Mean drainage values (mm/day) were calculated with APSIM and considered as the first estimate for recharge in the groundwater model. Given the piezometer records, most sites showed discharge (negative drainage) from surrounding land (Table1). In the process of the model calibration these initial values were adjusted accordingly.

Table 1. Values of drainage (mm/day) using APSIM and final recharge rates in MODFLOW (in brackets)

Zone	Sept99-March00	March00-Sept00	Sept00-March01	March01-Sept01
1	-0.2 (0.16)	0.11 (0.008)	-0.12 (0.16)	0.06 (0.008)
2	-0.4 (0.4)	0.11 (-0.1)	0.05 (0.4)	-0.05 (-0.1)
3	-1.4 (0.4)	-0.65(-0.4)	-0.2 (0.3)	-0.07 (-0.3)
4	-0.99 (0.25)	-0.45 (-0.1)	0.001 (0.4)	-0.09 (-0.01)
5	-0.6 (0.65)	-0.27 (0)	-0.27 (0.65)	-0.27 (0)

2.2. 3-D Model

The groundwater balance for different zones and clusters of farms were obtained by calibrating the groundwater flow model of the Coleambally area building on previous regional modeling using USGS, MODFLOW (Khan *et al.* 1999 and 2000). This model was applied to an area of 618,750 ha which was discretised into squares of area 1250m x 1250m. This discretisation resulted in 60 columns and 66 rows. Vertically the mesh squares consisted of four layers (upper Shepparton, lower Shepparton, Calivil and Renmark formations). Groundwater pumping data for the 1999-2001 period were used for this analysis. Observation records for more than 200 piezometers were considered in the model calibration. Records for possibly blocked piezometers or boreholes close to pumps were not considered for comparison with the predicted groundwater heads. Six-monthly data (stress periods) were used as model inputs. The simulation period covered 2 irrigation seasons (September- March) and 3 non-irrigation seasons (March- September) with time steps of 10 days. Observations for the end of March 1999 were used as initial condition of the model runs. Model predictions for groundwater heads, based on initial estimates of parameters, were compared with the observation records and adjustments to recharge values were made for each stress period to get reasonable agreement between predictions and observations.

Four clusters of farms were identified as priority areas because of their high watertable condition. These clusters are shown in Figure 3 and were used for water budget calculations at the end of each stress period. For the top groundwater layer (upper Shepparton) horizontal inflows and outflows (ML), recharge (+) and discharge (-) in ML/ha and exchange with lower layers (leakage, (+) downward) in ML/ha are of interest in each cluster.

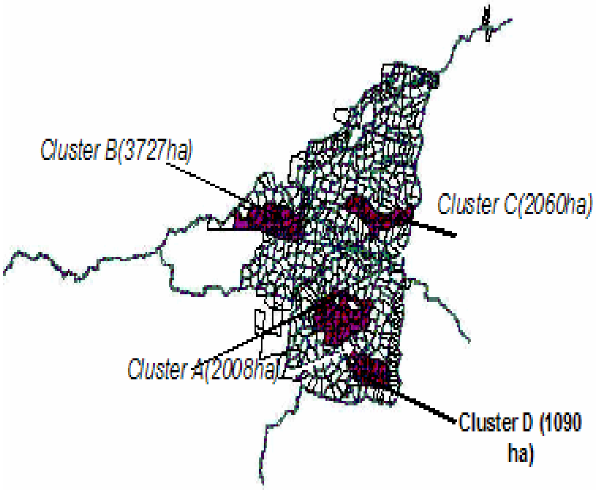

Figure 3. Map of priority farm clusters in the CIA

3. RESULTS AND DISCUSSION

3.1. 1-D Model to Develop Local Water Balance

Table 1 shows the results of 1-D modeling in terms of six-monthly mean drainage values from the bottom of the profile together with the final recharge values in the groundwater flow model. Most drainage values from the 1-D model were negative during irrigation and non-irrigation periods which was due to the fact that with the 1-D modeling and fixed bottom boundary conditions, irrigation on the surrounding land caused the watertable rise and hence negative recharge. These negative values indicate risk of salinisation. Zone-1 has no risk of salinisation due to the lowest net vertical capillary upflows because of relatively deeper groundwater depth and groundwater pumping in and around the zone. Zone 2 has low risk of salinisation while Zones 3, 4 and 5 have the highest risk of soil salinisation due to net vertical capillary upflows.

While the results of 1-D modeling show drainage below the bottom of the profile, this drainage may become recharge to groundwater, or it may also take other paths as lateral flow or regolith storage. Also with APSIM simulations, no crop was represented whereas in MODFLOW mixed landuse was represented through recharge and discharge processes. These explain some of the differences between the recharge estimates in table 1. Possible sources of errors in the 1-D estimates are soil characterization and piezometer readings while errors in the 3-D modeling might source from aquifer parameters and recharge estimates.

These results are not directly applicable for regional management because they only depict the 1-D groundwater dynamics and were only used as initial estimates in the 3-D modeling. A possible way forward is to carry out APSIM simulations for all landuses and soil types and find weighted averages for recharge on each cluster of farm. However, this would require an extensive piezometric network corresponding to each landuse and soil type which was beyond the scope of this study.

3.2. 3-D Model to Develop Regional Water Balance

Aggregated groundwater budgets for the four farm clusters of Figure 3 were obtained using the Coleambally MODFLOW model runs after calibration against more than 200 piezometer records. These water budgets for the top groundwater layer and for two stress periods are shown in Figures 4 and 5. Horizontal inflows and outflows (ML), recharge (+) and discharge (-) in ML/ha and exchange with lower layers (leakage, + upward) in ML/ha are shown for each farm cluster. Groundwater budgets (in ML) for all periods are also summarized for all clusters in table 2.

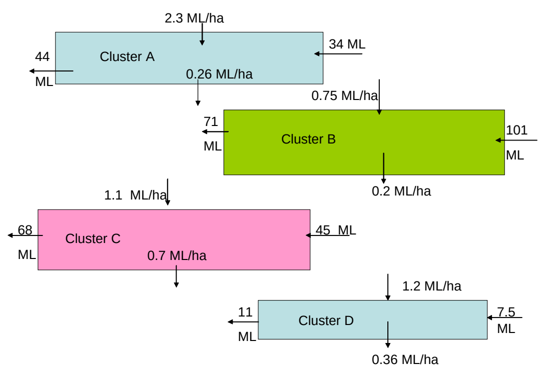

Figure 4. Groundwater budgets for September 2000- March 2001 (irrigation period)

All clusters show a consistent pattern of recharge during the irrigation season and discharge during non-irrigation period. The highest lateral groundwater inflow corresponds to the farm cluster "B" in the western part of the CIA indicating a greater risk of salinisation due to recharge from surrounding areas.

The water balance comparison shows that farm cluster "C" located in the center of the CIA has the highest vertical leakage (0.5 to 0.7 ML/ha/6 months) between the shallow and deeper aquifers. The farm cluster "B" located in the west of the CIA has the lowest vertical groundwater leakage (0.2 ML/ha/6 months) and is a net groundwater importer due to local recharge.

For all areas, lateral flow is only a small fraction of the total flow (table 2) and most outflow from the groundwater is through vertical leakage to the deeper aquifer or through capillary upflow.

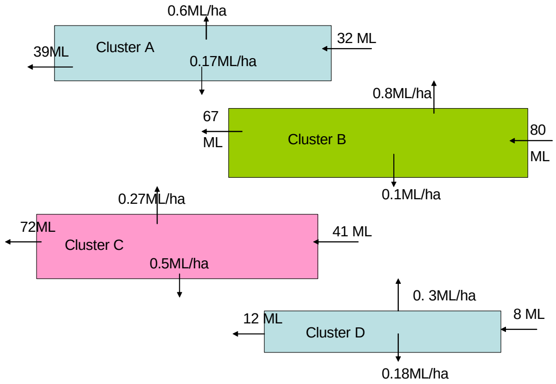

Figure 5. Groundwater budgets for March-September 2000 (non-irrigation period)

Table 2. Groundwater budget for cluster of farms

Period	Water Balance Component (ML)	Cluster A	Cluster B	Cluster C	Cluster D
Mar99-Sep99	*Horizontal Inflow*	34	45	39	10
	Horizontal outflow	46	62	124	16
	Recharge(+)/Discharge(-)	-120	-2273	-535	-33
	Leakage	542	484	1236	251
Sep99-Mar00	*Horizontal Inflow*	36	60	36	9
	Horizontal outflow	40	68	106	15
	Recharge(+)/Discharge(-)	2811	3541	2266	807
	Leakage	502	671	1442	305
Mar00-Sep00	*Horizontal Inflow*	32	80	41	8
	Horizontal outflow	39	67	72	12
	Recharge(+)/Discharge(-)	-1205	-2982	-556	-327
	Leakage	341	373	1030	196
Sep00-Mar01	*Horizontal Inflow*	34	101	45	7.5
	Horizontal outflow	44	71	68	11
	Recharge(+)/Discharge(-)	4618	2795	2266	1308
	Leakage	522	745	1442	392
Mar01-Sep01	*Horizontal Inflow*	31	114	55	7
	Horizontal outflow	49	71	46	9
	Recharge(+)/Discharge(-)	-361	-2236	-556	-33
	Leakage	120	596	989	251

During the irrigation period (September –March), the recharge usually exceeds the downward leakage and horizontal outflow is not enough to carry the extra water out of the area. This leads to net recharge, groundwater rise and associated problems of waterlogging and salinity. As a result, areas like cluster B and A in the west and south regions show signs of high watertables (Figure 6) and high groundwater salinity (Figure 7).

Cluster B is at the highest risk of salinization with high rate of recharge, lowest rate of leakage and due to higher capillary outflows from the saline watertable surface. There is a need to implement net recharge management on a priority basis to the farms within this region with a target for on-farm recharge reduction of 0.5 ML/ha. This can be achieved through a variety of on farm options such as using winter cropping to increase evapotranspiration, as well as improving water use efficiency of rice by limiting rice water use to the crop water requirement, and allowance for soil water storage and groundwater outflow rate. Drainage options combined with sequential reuse sometimes referred to as Serial Biological

Concentration (SBC) could be beneficial here. SBC is a management system that is based on the serial re-use of tile drainage effluent, cascading water through a series of crops with final containment in an evaporation basin. During the serial re-use cycles, the volume of effluent is reduced while the salinity increases, resulting in a relatively small volume of highly saline effluent for disposal in a small evaporation basin.

Cluster C with more than 2000ha of farm land and located in the central region in CIA has a high rate of leakage (0.5 to 0.7 ML/ha) from the shallow to deep aquifers. Although the water table depths are close to the surface at some places (Figure 6), the shallow groundwater in the eastern parts is less saline (Figure 7). Groundwater pumping and conjunctive use of surface and groundwater might be a good option in this region. Shallow watertable in this cluster of farms means that in order to control the watertable within an acceptable depth, the net recharge should be managed on farms and be reduced to less than the total outflow capacity of the shallow aquifer.

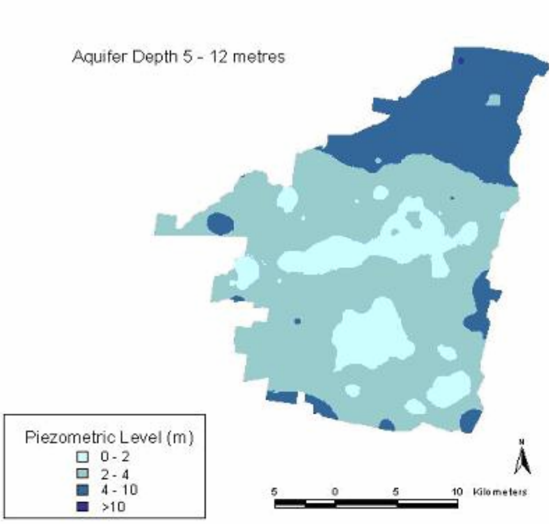

Figure 6. Watertable depths in CIA

Clusters A and D in the south region are associated with low vertical groundwater leakage and higher recharge rates (Table 2, figure 4). Like cluster B in the west, this area is also at highest risk of soil salinisation due to net vertical capillary upflows. Shallow saline watertables are already evident in this region (Figures 6 and 7). There is a need to implement net recharge management with the objective to reduce recharge by improving on-farm water use efficiency, winter cropping and drainage on these farms. Drainage options combined with the evaporation basins and serial biological concentration of salts should be considered in parts of this region.

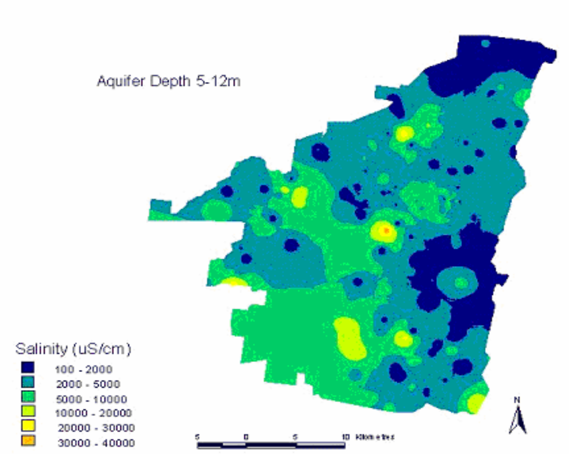

Figure 7. Groundwater salinity in CIA

Considering an average net recharge of 0.25-0.3 ML/ha in the CIA there is a need to reduce total recharge by around 20,000 to 25,000 ML/year through a combination of on-farm and regional management options.

4. CONCLUSIONS

The analysis in this study has given shallow groundwater budgets of farm clusters in the CIA using a combination of 1-D and 3-D modelling. In particular, recharge and discharge values and vertical and lateral groundwater outflow capacity are given for identifying areas at highest risk of soil salinization. On a regional basis the overall vertical leakage capacity between the shallow and deeper aquifers (0.2-0.7 ML/ha) should be matched with the overall irrigation and rainfall recharge to maintain current groundwater levels.

Since groundwater levels in some regions e.g. south and west are already within the root zone there is a need to initially reduce total groundwater recharge to less than the aquifer outflow capacity. These discharge areas (clusters B, A and D) have the highest risk of soil salinization due to limited outflow capacity and net vertical capillary upflows.

Management of net recharge for controlling watertables requires actions to be taken on-farm as well as on a regional scale. On the farm scale, improvements in farm water use efficiency, use of, permanent pasture and winter cropping can be beneficial. On a more regional basis, drainage combined with reuse and Serial Biological Concentration, groundwater pumping and conjunctive use can help reduce recharge and control the watertable below crop root zone. There is a need to quantify wider environmental benefits e.g. reduced saline flows to natural streams, protection of ecosystem services in and around the CIA as a result of implementation of the Land and Water Management Plan.

APSIM results indicate risk of salinisation due to most drainage values being negative indicating upward flow. APSIM and MODFLOW Fluxes at the watertable did not match directly, but in most cases were of the same order of magnitude (ignoring the direction of flow) with the difference being in the land use consideration (i.e. fallow land in APSIM simulations). To represent recharge for mixed landuse in MODFLOW cells there is a need to acquire detailed data for each landuse and soil type and carry out APSIM simulations which was beyond the scope of this study.

Although the results from APSIM are not directly applicable for regional management, the mean drainage values in each zone, can serve as first estimates of recharge into the regional groundwater model and provide a cross check on the relative magnitude of recharge. The calibrated MODFLOW model was then used to quantify outflow capacity of each cluster of farms and hence explore possible management options for control of waterlogging and salinity.

4. ACKNOWLEDGMENTS

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