Technical Constraints to Deep Groundwater Pumping for Conjunctive Water Management in the Coleambally Irrigation Area, Australia

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ABSTRACT

Coleambally Irrigation Area (CIA) of Australia has a complex multi-layered aquifer system. The upper shallow aquifers consist of discontinuous sand units, which are inter bedded with sequences of silts and clays. The shallow aquifer salinity is ranges 1,000 to more than 20,000 µS/cm. The silt and clay sequences act as aquitards overlying the deeper, more permeable aquifers, which contain fresh water with salinity less than 1,000 µS/cm.

The conjunctive management of water involves efficient use of surface water, additional irrigation supplies from the deep aquifers, and possible management of shallow watertables through shallow or deep pumping. The major constraint to pumping from the deep aquifers is the risk of enhanced leakage of the overlying saline waters from the shallow aquifers through aquitards into the deep aquifers. A groundwater modelling investigation was undertaken to assess safe deep bore locations and rates of pumping to supply additional irrigation supplies without increasing the deep aquifer salinity. The study also analysed whether deep pumping could play a significant role in watertable and salinity control at the surface. The results found that judicious pumping could be undertaken with only small increases in the deep aquifer salinity; however, the impact on watertables was negligible. Thus deep groundwater pumping can provide additional suitable water supplies but cannot be an effective watertable/salinity control measure in the CIA.

INTRODUCTION

Coleambally Irrigation Area (CIA) is part of the Murray Darling Basin and is located within the lower part of the Murrumbidgee River Catchment in southeastern Australia (Figure 1). The CIA comprises of an area of 79,000 ha south of the Murrumbidgee River in the Lower Murrumbidgee region of NSW. The area was originally settled in the 1840s and was predominantly used as pastoral land (Coleambally Land and Water Management Plan 1996). The groundwater pressures in the CIA remained relatively unchanged until the advent of irrigation in the 1960s when 333 farms were allocated 79,000 ha to form the CIA. The main irrigated enterprises in the area are rice, sheep/annual pastures, winter crops, soybeans and some horticulture. By far the most prevalent land use is rice. Rice is grown under pounded conditions, thus use of much larger volumes of water per hectare (~14 ML/ha) than other crop types (Wheat 3.6 ML/ha, Soybeans 9.5 ML/ha). Average total

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annual rainfall in the Lower Murrumbidgee region decreases slightly from east to west and lies in the range of 400-450mm/yr. The annual evaporation varies between 1500-2000mm.

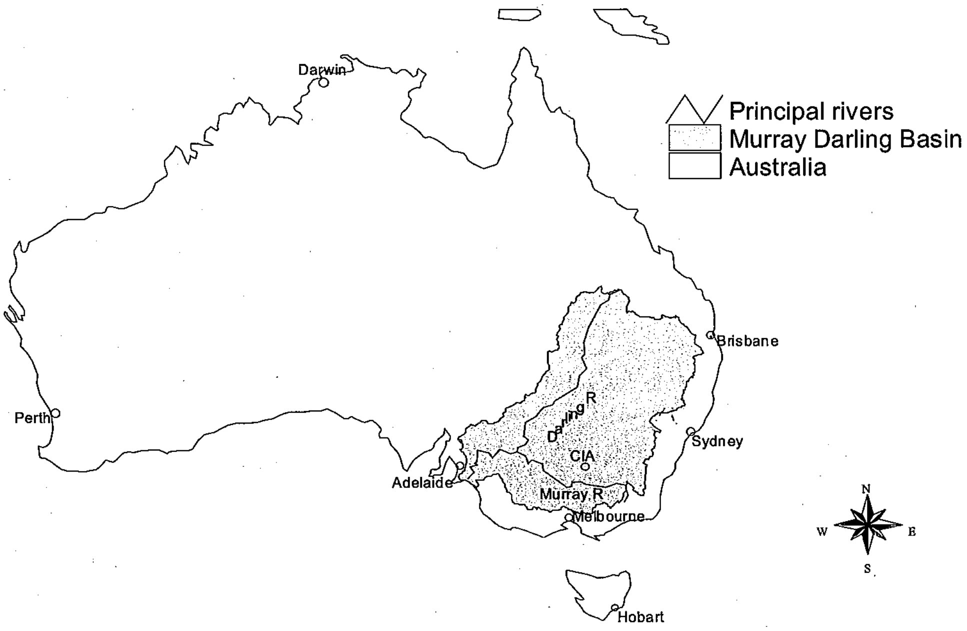


Figure 1: Location of Coleambally Irrigation Area

The average surface water supplies to the CIA are around 400 GL/yr. The water balance estimates for CIA (Coleambally Land and Water Management Plan 1996) suggest that the total amount of water entering the shallow groundwater system is about 54 GL/yr (average over 1985-1995). Of this, 14 GL/yr moves away from the area laterally, and 26 GL/yr flows downwards into the deep groundwater system. The remaining 14 GL/yr is the volume assumed to cause rising groundwater levels. The downward flow to deeper aquifers may result in higher groundwater potentials in deeper aquifers (in the absence of significant pumping) and therefore reduced potential gradients between shallow and deeper aquifer systems. The reduced groundwater gradients between the shallow and deep aquifers may result in decreased downward flows in future and therefore a greater rate of watertable rise for similar recharge.

Prior to irrigation development, water tables in the area were around 15-20 m below the ground surface. Since irrigation began water levels have risen at rates up to 1m /year with the effect that now a large groundwater mound exists beneath the CIA. In 1999 around 2/3rd of the CIA had water tables within 2 m of the ground surface. Rising water tables with their associated effects of waterlogging and soil salinization are threatening the agricultural productivity and environmental sustainability of the area. Conjunctive water management in CIA can involve measures, which can reduce recharge (efficient use of irrigation water) or can induce discharge (e.g. shallow or deep groundwater pumping) from the groundwater. Groundwater pumping and reuse is a possible way of water table control. One major constraint in the groundwater use is its quality. Water quality in the shallow aquifers is extremely variable (1,000-30,000 μS/cm), and in general, shallow groundwater is of too poor a quality to be considered as a resource. Deep groundwater, however, are generally of a good quality (500-700 µS/cm). Deep groundwater pumping thus can serve both as resource and water table/salinity control. The deep groundwater can be used conjunctively with the surface water to improve the environmental sustainability of the CIA. This paper describes a modelling study undertaken to explore the feasibility of deep groundwater pumping for conjunctive water management in the CIA.

HYDROGEOLOGY OF CIA

The apex of the Murrumbidgee alluvial fan is situated near Narrandera (Wooley and Williams, 1978). The sediments of this fan increase in thickness in a westerly direction from the eastern flank of the basin. Brown and Stephenson (1991) categorised these sediments based on age and type of deposition into three distinct units, these being Renmark, Calivil and Shepparton formations.

The Renmark formation is the oldest stratigraphic unit and directly overlies the pre-Cainozoic bedrock. It was deposited during the Palaeocene to Middle Miocene ages. The base of the Renmark formation consists of light brown quartz sand (Warina Sand), the upper sequence consists of more argillaceous and carbonaceous sediments (Olney Formation). It is estimated that 30 to 50% of the Renmark formation is comprised of sand. The horizontal hydraulic conductivity of the Renmark formation averages between 10 and 30 m day-1 but it can be as high as 100 m day^{-1}.

The Calivil formation was deposited during the late Miocene to Pliocene ages and consists predominantly of pale grey coarse to granular quartz sand, with lenses of kaolin and carbonaceous clay. It is estimated that this formation consists of 50 - 70% sand and gravel. The average hydraulic conductivity of the Calivil formation estimated at Darlington point is approximately 130 m day^{-1}.

The Shepparton formation was deposited from the Pliocene age until present day. It consists of a matrix of clay, silt and silty clay, with lenses of fine to coarse sand and gravel. The clay is silty, variegated, mottled and red brown, yellow or white in colour. The proportion of sand in this formation is highly variable, but typically in the range of 10 - 30%. The geology of the Shepparton formation is complicated due to prior stream deposition, which resulted in localised concentrations of coarse grade sands and connections to deeper aquifers. Due to the discontinuous nature of Shepparton sand lenses the average hydraulic conductivity is around 2 to 3 m day-1 but it may be 25 to 100 m day-1 in the more sandy parts.

MODELING METHODS

Sustainable conjunctive water management is constrained by surface and groundwater availability and quality. If too much water enters the groundwater system then the land could be waterlogged, if too much water is removed from the groundwater system then the groundwater resource would be depleted and may be degraded by salt intrusion. The objective of sustainable conjunctive water management is to find an optimal combination of groundwater and surface water use that augments irrigation supply and also controls salinization and waterlogging.

In order to determine sustainable levels of surface water and groundwater use at a regional scale, the response of the groundwater system to changes in recharge rates and groundwater pumping rates needs to be determined. The best method of determining how a variable groundwater system will behave under variable conditions is to model the system. The MODFLOW (McDonald and

Harbaugh, 1988) model of the CIA, already developed by CSIRO (Enever, 1999, Khan et al, 1999), was improved by refining its calibration and adding solute transport options. Historical water salinity data was collected, collated and analysed and a MT3D (Zheng, 1990) solute transport model was developed and linked with the regional groundwater model. This combined regional groundwater and solute transport model was used to predict the response of the groundwater system to the deep pumping in terms of head and salinity changes. With the constraints of acceptable drawdowns and salinity changes a number of scenario were run to decide the possible location (s) of deep bore(s).

Figure-2 shows the layout of the finite difference grid used for the CIA model. The grid consists of 60 columns and 66 rows (1.25 km square mesh) and encompasses an area of 6,187.5 km^2. The eastern edge of the grid was set parallel to the bedrock. The southern edge was positioned to include Yanco Creek. The northern edge of the grid was set to include the Murrumbidgee river and was positioned far enough north of the Murrumbidgee to include the areas around Darlington Point to incorporate groundwater pumping over the last ten years. The western edge of the grid was set several kilometres outside the western limit of the CIA to minimise effects of boundary conditions on the groundwater regime in the CIA.

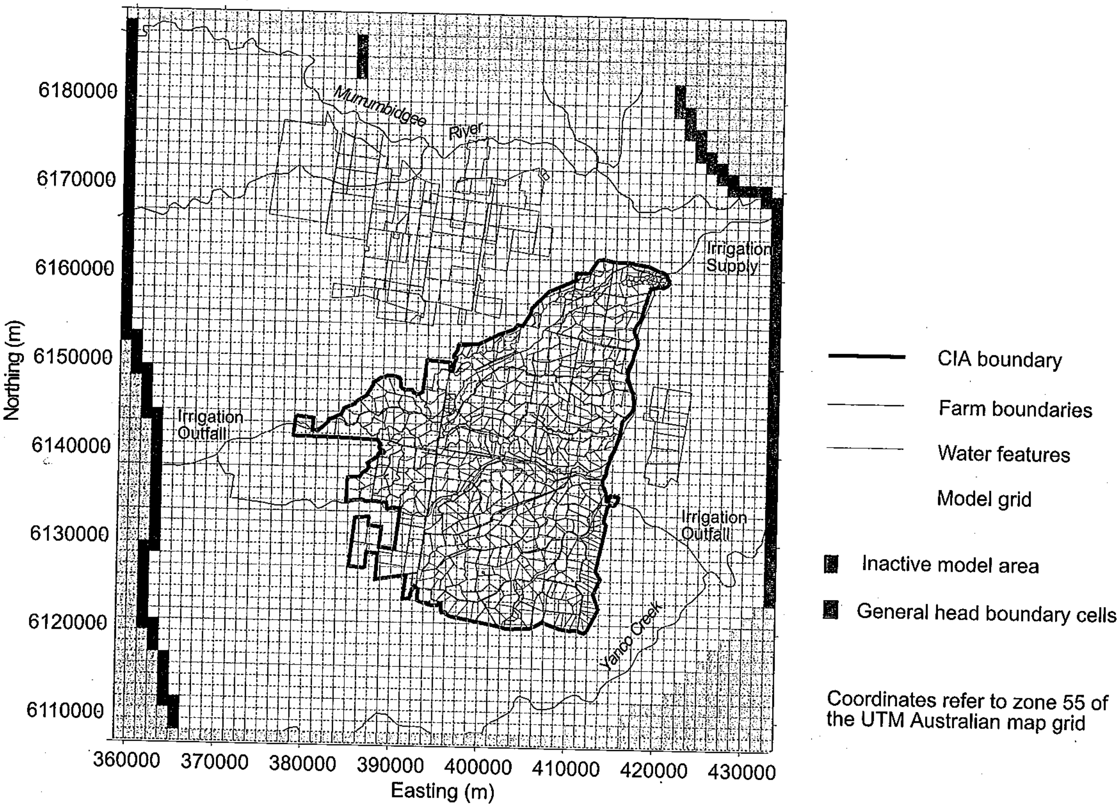


Figure 2: CIA model grid

The four layers represented in the CIA model were defined by the stratigraphic breakdown shown in Figure-3. The Shepparton formation was further divided into two separate model layers in order to improve the model's treatment of the vertical flow processes in the shallow aquifers. Kriging was used in the interpolation of all spatial data sets in the CIA model, using Surfer (Golden Software, 1994).

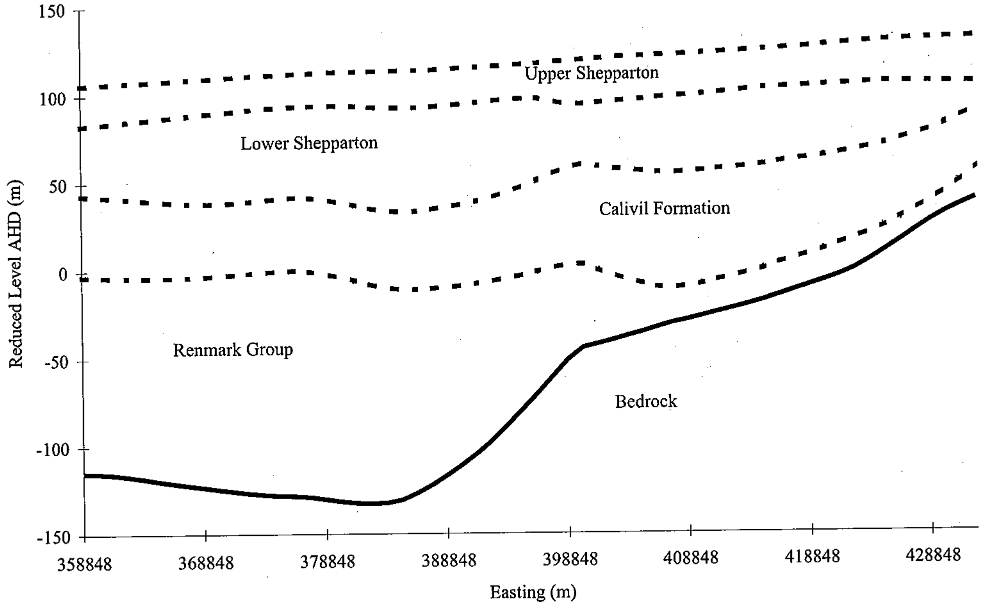


Figure-3 East to west transect through Northing 6149562 (m)

The CIA model simulation period was March 1985 to March 1995 using monthly stress periods and 10-day time steps. A trial and error procedure was adopted to calibrate the hydraulic parameters and recharge to match piezometeric water level hydrographs. Forty-three hydrographs were used to calibrate the CIA model, 14 in the Upper Shepparton, 12 in the Lower Shepparton, 8 in the Calivil and 9 in the Renmark. Figure-4 shows old and new calibration of the model at one of piezometers in the Calivil formation. Details of model recalibration can be found in Prasad et. al. (2001).

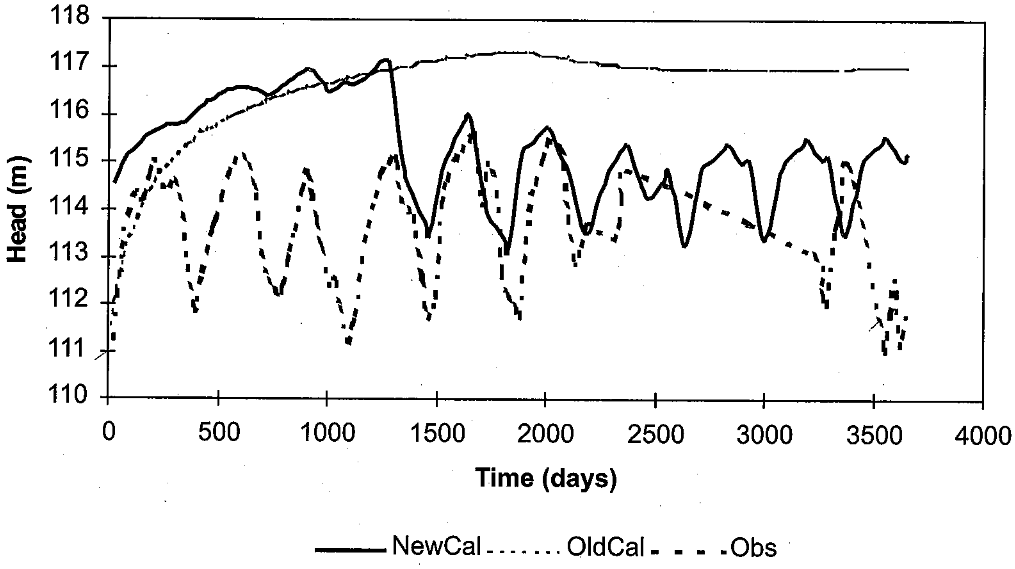


Figure 4 Old and new calibration at Piezometer GW030282_2 in Calivil Formation

Salinity Data Used in Transport Model

In 1973, major part of the CIA had shallow groundwater salinity less than 4000 µS/cm, which increased up to 8000 µS/cm over more than half of the CIA with some pockets showing salinity as high as 12000 µS/cm. Salinity in 1984 appears higher than in 1987, which might be more due to sampling different piezometers than any physical trend. The increase in salinity in the Lower Shepparton Aquifer is attributed to gradual rise to water table due to increase in recharge caused by irrigation.

The data in the Calivil formation is very scarce and are not really representative of the year, which they apparently refer to. As compared to the shallow layers, the water quality in the Calivil Aquifer is very good (around 700 µS/cm) and has not changed much.

The 1985 salinity level (< 650 µS/cm) shows that the Renmark Aquifer salinity is lower than that for the Calivil Aquifer.

Initial Conditions for the Solute Transport Model

As the flow model has been developed and calibrated for the period March 1985-March 1995, the March 1985 salinity was chosen as the initial conditions for the solute transport model. The initial condition for all layers was generated by Krigging the 1985 salinity data by the SURFER (Golden Software, 1994) software.

DEEP GROUNDWATER PUMPING SCENARIOS

Around 46000 ML /year is currently being pumped from the deeper aquifers in the modelled region. This volume includes approximately 6000 ML /year being pumped by a deep bore located within the CIA and owned by the Coleambally Irrigation Cooperative Limited (CICL). The CICL has an additional allocation of around 4000 ML/year from the deeper aquifer. The long-term impact of pumping from this additional allocation of water from deeper aquifers on salinity levels and drawdown in deeper aquifers and on drawdown in shallow aquifers is determined to help decide suitable location(s) of deep bore(s). The regional flow and solute transport model were run a many times to evaluate a number of feasible pumping scenarios. The aim was to maximize the drawdown in shallow aquifers with the constraint that quality of water coming from the deep groundwater well does not deteriorate excessively and also the instantaneous drawdown in deeper layers remains within some permissible limits. The flow and solute transport models were run in a forecast mode for 20 years starting 1995, with the new bore(s) introduced in August 2000 and operating for 8 months between August and March every year. Instead of using modelled output of 1995 as initial condition, the actual piezometric heads and salinity data (where ever available or combination of nearby years) were used to generate initial conditions. This was done to avoid the accumulation of computation errors. The recharge cycle between 1985-1995 was repeated twice assuming similar irrigation practices and meteorological conditions.

Figure 5 describes the locations of well (s) used for different scenarios. Table-1 shows the proportion of discharges assigned to the well from the Calivil and Renmark formations in a particular scenario. In all scenarios the total pumping volume remained constant at Q = 4000 ML/year. In scenario 1, one well was placed in the Calivil layer at around the centre of the southern district of the CIA. In scenario 2 the well was located at the same place as in scenario 1 but the pumping volume (Q = 4000 ML/year) was distributed between the Calivil and Renmark layers in the 30:70 ratio. In scenarios 3 and 4, the well was located near the eastern boundary of the CIA in the southern district. The difference between the scenario 3 and 4 was in pumping percentages from the Calivil and Renmark, whereas in scenario 3, the total pumping (100%) was from the Calivil layer alone. In scenario 4 pumping was distributed between Calivil and Renmark layers in the ratio of 50:50. In scenarios 5 and 6, two wells, one in the middle of the Southern CIA (at the same location as scenarios 1and 2) and another near the northwest corner of the southern CIA were used. Both wells were assigned half of the total volume of annual allocation (Q = 2 x 2000= 4000 ML/year). The difference between scenario 5 and 6 was that the abstraction volume distribution at both locations between the Calivil and Renmark was in the ratio of 30:70 in scenario 5, and it was in the ratio of 50:50 in the scenario 6. All these scenarios were developed by trial and error approach to achieve desired drawdown in upper aquifers and keep salinity changes within acceptable limits.

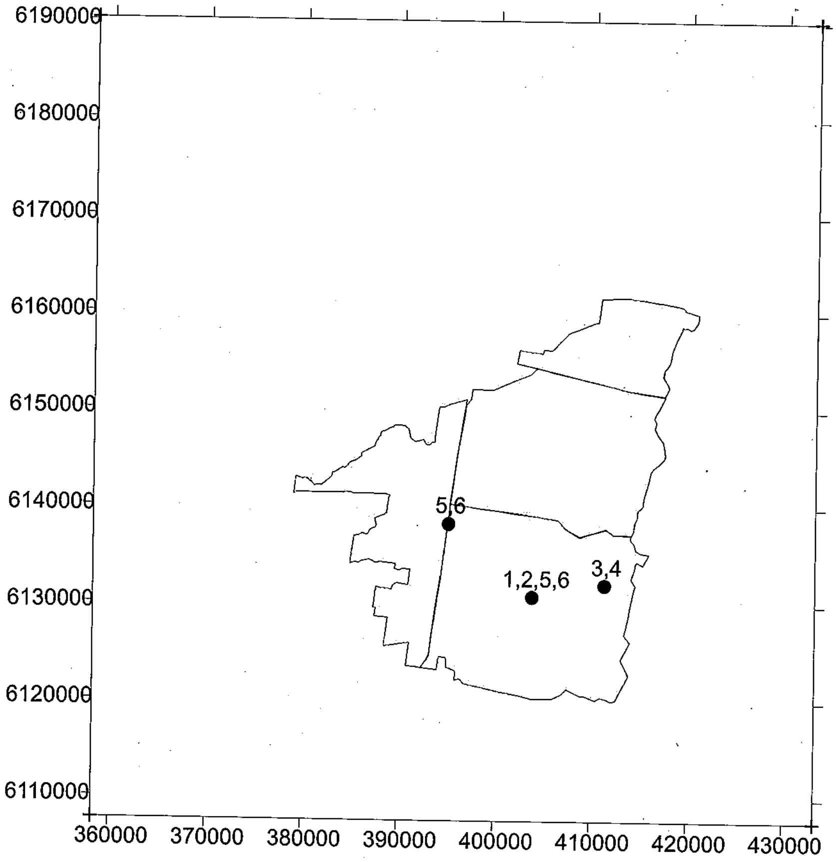


Figure-5 Location of deep well in different scenarios

Table 1. Percentage volumetric contribution of Calivil and Renmark in different scenarios. For * marked wells, volumes are equally distributed between two locations.

Scenario number	No. of wells	Q (ML/year)	Contribution (%) of Calivil	Contribution (%) of Renmark
1	1	4000	100	-
2	1	4000	30	70
3	1	4000	100	-
4	1	4000	50	50
5	2*	4000	30	70
6	2*	4000	50	50

RESULTS

In this section only a brief description of results is provided. Detailed results can be found in Prasad et al (2001).

Scenario-1

The hydrograph in the Calivil showed that there was an excessive local drawdown fluctuation (> 100 m) in the Calivil formation and the deep groundwater quality rapidly deteriorated (Figure 6). This scenario was considered infeasible.

Scenario 2

The spatial distribution of drawdown in the Calivil and Renmark formations showed that almost the entire CIA would have a minimum relative drawdown of 0.2m. The maximum relative drawdown at the well in these two layers was between 30-38 meters. The drawdowns, however, in these layers were cyclic i.e. aquifers more or less tend to fully recover as evident from their hydrographs. The residual drawdowns in these layers were less than 2 m at the end of 15 years of pumping. Thus aquifers were not getting mined. The residual drawdown in shallow aquifers at the end of 15 years of pumping was around 0.2 m. The effect of deep pumping on the drawdown in the shallow aquifers was although small but was indicative of a favourable long-term outcome i.e. enhanced downward leakage.

The temporal variation of salinity showed that the salinity of Calivil Aquifer would increase as a result of pumping at a rate of around 33 µS/cm/year. Given the availability of surface water for dilution, this increase may be acceptable from irrigation point of view.

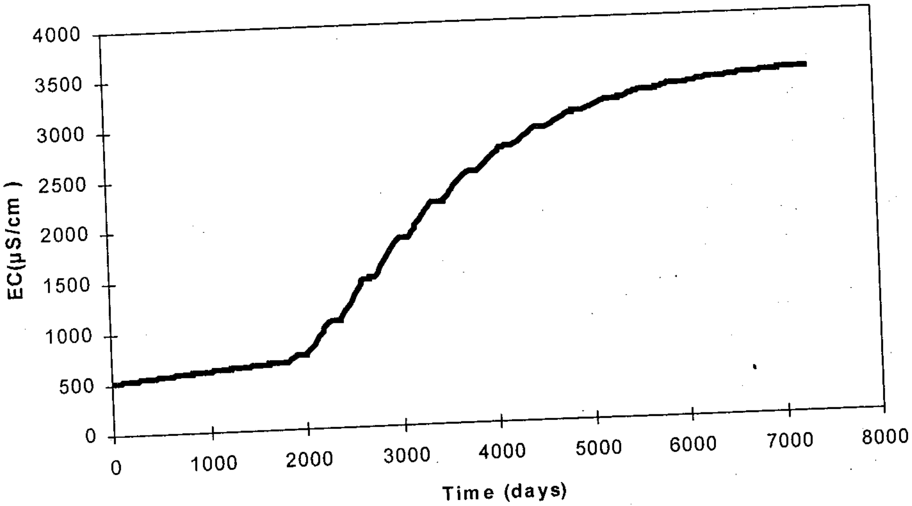


Figure-6 Temporal variation in Calivil Salinity at the pumping site for scenario-1

Scenario 3

Almost the entire CIA would be within the area of influence of a minimum relative drawdown of 0.2m in the Calivil and Renmark at the end of 15 years of pumping. However, the area of influence is smaller compared with the scenario 2. The residual drawdown in the Calivil Aquifer would be less than 2 m at the end of 15 years of pumping. The drawdowns in the shallow aquifers are concentrated around the eastern boundary of the CIA. The maximum shallow aquifer drawdown at the end of 15 years of pumping was between 2-5 m. The salinity of deeper aquifers would increase as a result of 15 years of pumping by around 450 μS/cm giving a moderate increase rate of around 30 μS/cm/year.

Scenario 4

Results of scenario 4 were similar to that of scenario 3.

Scenario 5

The Calivil and Renmark layers would experience a minimum relative drawdown of 0.2m over almost the entire CIA. The majority of areas in the southern and western CIA would experience 2-5 m drawdown. The maximum relative drawdown at the first well location in the deeper aquifers was between 17-20 meters and at the second well location was between 17-20 meters. These drawdowns were cyclic, as aquifers more or less tend to fully recover. The maximum drawdown in the shallow aquifers after 15 years of pumping was between 1-2 m. At the first well location, net increase in groundwater salinity over 15 years of pumping was around 120EC and at the second well location was around 160 μS/cm. The net rate of increase in salinity due to the pumping was small 8-11 μS/cm/year.

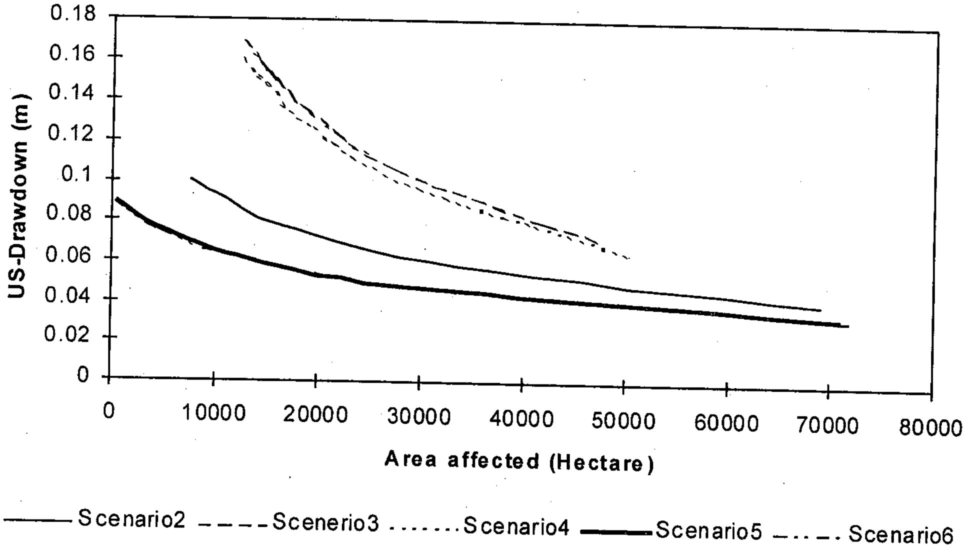
Scenario 6

Results of scenario 6 were similar to those of the scenario 5.

Relative Upper Aquifer Drawdowns

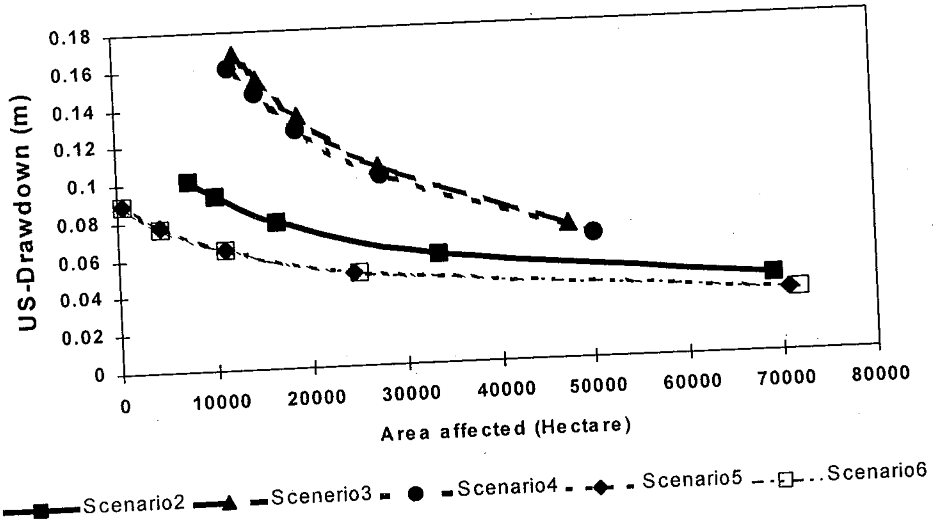
A summary of cumulative drawdown and area of influence in shallow aquifers is given in Figure-7. The drawdown area curves shown on these graphs are the spatial average values. It is evident that scenarios 3 and 4 are causing greater lowering of water table over a smaller area than scenarios 5 and 6, which are identical. The scenarios 5 and 6 tend to lower water table by smaller amounts but over much larger area. The scenario 2 is placed in between the two extremes.

Figure-7 Shallow aquifer drawdown versus area affected for different scenarios



CONCLUSIONS

Groundwater pumping from two well locations (Scenario 5) appears to provide best option for the long-term sustainability of water quality in deep aquifers but offers little advantage in terms of water table control. Total pumping from one well (scenarios 3 and 4) appears to be more effective in controlling water table over a smaller area, but it can result in greater degree of quality deterioration. The scenarios 5 and 6, where two wells are employed, have more operational flexibility than any other scenario, which employ only one well. A better quality of water was obtained in case of pumping from both the Calivil and Renmark formations rather than pumping from the Calivil alone. Though the scenarios 5 and 6 result in a very little water table control, it is recommended, because of the long term quality sustainability of the deeper aquifers, that pumping from the deeper aquifers should be treated as additional irrigation supply rather than a true water table control measure. The water table can be better controlled by improving water use efficiency and exploring shallow drainage options.



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