CHAPTER 8

MANAGEMENT STRATEGIES FOR MINJUR-MOUTHAMBEDU AQUIFER SYSTEM

8.1 INTRODUCTION

The aim of this research is to develop a methodology for the solution of an integrated management model for the reclamation of sea water intruded aquifer. This model accounts for nonlinearities associated with the flow, solute transport equation and other nonlinearities associated with objective function and constraints. Performance evaluation of the developed methodology along with its applicability and suitability in evolving a time varying regional groundwater management strategy is discussed in detail.

Regional management of groundwater resources must consider quality and quantity aspects together. Simulation of the flow and solute transport process is highly nonlinear, especially when stresses are increased or decreased. These nonlinearities necessitate the application of nonlinear programming technique for the solution to the integrated management model.

An integrated groundwater management model and a methodology for its solution using the nonlinear programming (NLP) technique with simulation model is developed and tested with application to a field problem. In this formulation, the simulation model is linked explicitly to the management model as an independent module. The simulation module is
treated as a subroutine that is called by the optimisation procedure. The simulation model is a separate, efficient and testable module. Numerical difficulties with simulation model may be worked out prior to management model execution and therefore does not endanger the convergence of optimisation procedure. Once simulation model for a particular system has been developed, implementation of management model is easier. There is no need to evaluate the Jacobian matrix because it is an unconstrained nonlinear optimisation. The proposed management model is formulated as a multivariable constrained nonlinear optimisation problem and penalty is applied to convert the constrained optimisation problem into an unconstrained problem. To simulate the physical and chemical processes occurring within a confined aquifer system, MODFLOW and MT3D models are used separately. The pattern search algorithm proposed by Hooke and Jeeves (Rao, 1991) is used to solve the resulting unconstrained optimisation problem.

The Hooke and Jeeves model acts as a driver model wherein it calls the simulation model by passing the management decision variables like recharge quantity and gets back the corresponding objective function value. The NLP model then adjusts the management decision variables, gets a new objective function value and moves to the better point. This process repeats till there is no further improvement in the objective function by altering the decision variables.

8.2 FORMULATION OF THE OPTIMISATION PROBLEM AND SOLUTION METHODOLOGY

A key component of simulation-optimisation modelling is the formulation of the optimisation problem that requires definition of management objective, decision variables and management constraints. In this work, the goal is to reduce the salt concentration at the critical zone. This can be achieved through two formulations. One is to find the optimal reduction in the pumping and the other is by optimal recharge for which the concentration is reduced at the end of planning horizon.
8.2.1 Decision Variables

Definition of the optimisation problem includes decision variables whose values will be determined as part of the optimisation solution. In a remediation system, there are two sets of variables. They are decision variables and state variables. Decision variables include the pumping and injection rates for the wells. Other possible decision variables include well locations. The purpose of the design process is to identify the best combination of these decision variables. The state variables are the hydraulic head and the chloride concentration. Any remediation design model shall include two major components. The simulation model updates the state variables and the optimisation model selects the optimal values for the decision variables.

8.2.2 Managerial Constraints

The formulation of optimisation problem includes the definition of management constraints. Usually the constraints are placed on the piezometric heads, total recharge (or pumping) and chloride concentration in the case of quantity and quality management problems. The solute considered here is chloride, a conservative pollutant.

i. The temporal and spatial distribution of piezometric heads are stated such that it should not drop below the specified minimum values and the same should not rise above the specified maximum values.
ii. Total recharge (or pumping) must be within the specified range.

\[ (R)_{ij}^k \leq (R_{ub})_{ij}^k \]  

(8.2)

iii. The temporal and spatial distribution of pollutant concentrations should not exceed the specified threshold values so that the water quality standards in the aquifer will not fall below the specified value (usually zero) and the concentrations for the intended use

\[ (c)_{ij}^k \leq (c_{ub})_{ij}^k \]  

(8.3)

Here \( h_{lb}, R_{lb}, \) and \( c_{lb} \) are the lower bounds on hydraulic head, artificial recharge and concentration, whereas \( h_{ub}, R_{ub}, \) and \( c_{ub} \) are the upper bounds on hydraulic head, pumping and concentration, respectively and \( k \) denotes the time step.

### 8.2.3 Objective Function

In most of the pollutant management problems, the goal is to find either the minimum recharge quantity or minimum reduction in pumping that satisfies a set of constraints to maintain the head, recharge and concentration in a specified range. To modify the formulation of the unconstrained nonlinear problem, the constraints are brought into the objective function through penalties. The objective function can be written as

\[
\text{minimise } \sum ph \cdot dh + \sum pc \cdot dc + \sum pr \cdot dr \quad \forall i,j,k
\]  

(8.4)

where,

\( dh \) is the deviation of the head from the specified range at locations \((i,j)\),
is the deviation of the concentration from the specified range at locations (i,j),
is the deviation of the recharge from the specified range at locations (i,j)
is a set of specified locations and
is the number of time steps considered within a planning horizon.
is the penalty for head deviation
is the penalty for concentration deviation
is the penalty for recharge deviation

8.2.4 Method of Solution

To find the optimal solution, the constrained problem is transformed into an unconstrained problem using penalty application. The unconstrained nonlinear problem is then solved using the Hooke and Jeeves (HJ) method which is a direct search technique. After transforming the constrained nonlinear optimisation model into unconstrained nonlinear optimisation model, the solution is obtained by solving the unconstrained formulation. Several methods are available for solving an unconstrained minimisation problem. These methods can be classified into two broad categories as direct search methods and descent methods.

Direct Search methods require only objective function evaluations and do not use the partial derivatives of the function in finding the minimum and hence called the nongradient methods. In addition to the function evaluations, the descent techniques require the evaluation of first and higher order derivatives of the objective function. So the descent techniques are also known as gradient methods. Each method has its own merits and demerits. Due to the nonconvexity inherent in many field problems, there may be multiple optimal points in the solution domain.
There is no guarantee that the solutions based on the gradient methods are the globally best ones.

All the direct search methods are iterative in nature and hence they start from an initial trial solution and proceed towards the minimum point in a sequential manner. It is important to note that all the unconstrained minimisation methods (a) require an initial point $x_i$ to start the iterative procedure and (b) differ from one another only in the method of generating the new point $x_{i+1}$ (from $x_i$) and testing the point $x_{i+1}$ for optimality.

The various methods available (Rao, 1991) to solve such unconstrained models are Hooke-Jeeves (HJ), Powell's Conjugate Direction, Fletcher-Reeves, Polak Ribiere, Davidon-Fletches-Powel and Broyden-Fletcher Shanno and Bisection methods. All of these methods except HJ, Powell's Conjugate Direction and Bisection methods require derivatives of the composite objective function. It is difficult to obtain derivatives of a highly nonlinear, complex and dimensionally large composite objective function. Finding the derivatives numerically requires more computer time and approximations. The HJ method in conjunction with the Penalty Function Method is preferred over other approaches, because evaluation of derivatives are not required and most computational difficulties associated with solving the large nonlinear optimisation problem are eliminated. Implementation of the HJ method is simple and straight forward. It is not adversely affected by sparse constraint matrices. Also, computational difficulties like inconsistencies between composite objective function and derivative values, non-differentiability and invalid arguments do not arise in this method. These difficulties may arise in other methods of unconstrained nonlinear optimisation, especially gradient based methods. The other advantage of the HJ method is that it requires less computer memory as it is not required to store information regarding search directions during the exploratory search or pattern move.
8.2.4.1 Bisection method

For unimodal and one dimensional optimisation problems, the simplest technique one can think of is the bisection method. In this method, for two extreme boundary points and for the exact mid point, the function values are evaluated. Then the function values are evaluated for the middle points of each half. By knowing the function values at these five points, one half of the space can be eliminated from the search based on the minimisation or maximisation condition. If the problem is a minimisation problem, the half that has higher function value at its middle point is eliminated from search. These steps are repeated for the selected half. This process is to be continued till the convergence is achieved or the length of last half in the search space is less than a predefined value. As this method, eliminates half of the space domain in each cycle, this method is called as bisection method.

8.2.4.2 Hooke and Jeeves method

Hooke and Jeeves method is a sequential technique where each step consists of two kinds of moves, one called the exploratory move and the other called the pattern move. The first kind of move is included to explore the local behaviour of the objective function and the second kind of move is included to take advantage of the pattern direction.

The general procedure can be described by the following steps.

1. Start with an arbitrarily chosen point

$$X_1 = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ \vdots \\ x_n \end{bmatrix}$$
Called the starting coordinate direction $U_i$
where $i = 1, 2, \ldots, n$. Set $x=1$.

2. Compute $f_k = f(X_k)$. Set $i=1$, $y_{k0} = x_k$ and start the exploratory move as stated in step 3.

3. The variable $x_i$ is perturbed about the current temporary base point $Y_{k,i-1}$ to obtain the new temporary base point as

$$Y_{k,i} = \begin{cases} 
Y_{k,i-1} + \Delta x_i U_i & \text{if } f^* = f(Y_{k,i-1} + \Delta x_i U_i) \\
Y_{k,i-1} - \Delta x_i U_i & \text{if } f = f(Y_{k,i-1} - \Delta x_i U_i) \\
Y_{k,i-1} & \text{if } f = f(Y_{k,i-1}) < \min(f^*, f)
\end{cases}$$

This process of finding the new temporary base point is continued for $i = 1, 2, \ldots, n$ perturbed to find $Y_{k,n}$.

4. If the point $Y_{k,n}$ remains same as $X_k$, reduce the step lengths $\Delta x_i$ (say, by a factor of 2), set $i=1$ and go to step 3.

If $Y_{k,n}$ is different from $X_k$, obtain the new base point as

$$X_{k+1} = Y_{k,n}$$

and go to step 5.
5. With the help of the base point $X_k$ and $X_{k+1}$, establish a pattern direction $S$ as

$$S = X_{k+1} - X_k$$

and find a point $Y_{k+1,0}$ as

$$Y_{k+1,0} = X_{k+1} + \lambda S$$

Where $\lambda$ is the base length which can be taken as 1 for simplicity. Alternatively, we can solve a one dimensional minimisation problem in the direction $S$ and use the optimum step length $\lambda^*$ in place of $\lambda$ in equation (8.6).

6. Set $k = k + 1$, $f_k = f(Y_{k,0})$, $i = 1$ and repeat step 3. If at the end of step 3, $f(Y_{k,n}) < f(X_k)$, we take the new base point as $X_k + 1 = Y_{k,n}$ and go to step 5. On the other hand, if $f(Y_{k,n}) > f(X_k)$, set $X_{k+1} = X_k$, reduce the step lengths $\Delta X_i$, set $k = k + 1$, and go to step 2.

7. The process is assumed to have converged whenever the step lengths fall below a small quantity $\epsilon$. Thus the process is terminated if

$$\max (\Delta x_i) < \epsilon$$

8.3 APPLICATION OF THE MANAGEMENT MODEL

To manage the MMAS, the above discussed formulation is used with known aquifer parameter values and for the known initial and boundary conditions. The solution of the model provides the distributed pumping and recharge strategy that optimises the objective function while attempting to meet all imposed constraints.
8.3.1 Scenario 6: Optimal Reduction in Pumping

The aim of this formulation is to find the optimal reduction in the irrigation demand by maintaining the constraints on the head and concentration. This scenario is attempted to know the percentage of pumping in the year 1996 that can reclaim the aquifer optimally. Initially the constraints are kept on both heads and concentrations. After a number of trials, it was found that the reduction in the pumping is directly proportional to the cleanup criteria. The optimal pumping is the zero pumping for which maximum cleanup takes place. But for zero pumping the piezometric pressure heads are increased to +44 m (Scenario 5) which is not practicable. Hence the constraints are set only on piezometric heads, and thus the decision variable is pumping quantity.

The objective function which constitutes the unconstrained minimisation problem for the proposed management model can be expressed as

\[
\text{minimise } \sum \text{ph} \cdot dh \quad \forall \ ij, k
\]  
\[ (8.8) \]

8.3.1.1 Penalty values

The piezometric head \( h_{ij} \) is constrained in the range of 0.5 to 1 m, since the piezometric head if above the mean sea level prevents the sea water intrusion. The penalty for the deviation from this range is taken as follows.

<table>
<thead>
<tr>
<th>Head h (m)</th>
<th>Penalty (ph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h &lt; 0.5 )</td>
<td>( (0.5-h) \times 10 )</td>
</tr>
<tr>
<td>( 0.5 \leq h \leq 1.0 )</td>
<td>0</td>
</tr>
<tr>
<td>( h &gt; 1.0 )</td>
<td>( (h-1.0) \times 10 )</td>
</tr>
</tbody>
</table>
8.3.1.2 Results of scenario 6

The optimal reduction in pumping is 28 percent for which the penalty value is 623. All the other neighbouring points show higher penalty values as shown in the Figure 8.1.

<table>
<thead>
<tr>
<th>Year</th>
<th>Minimum head (m)</th>
<th>Concentration at 6.5 km (mg/l)</th>
<th>Position of 1000 mg/l isochlor (km)</th>
<th>Distance moved by 1000 mg/l isochlor (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>-8</td>
<td>8329</td>
<td>9.95</td>
<td>-</td>
</tr>
<tr>
<td>2005</td>
<td>-0.38</td>
<td>6458</td>
<td>8.81</td>
<td>- 1140</td>
</tr>
<tr>
<td>2010</td>
<td>0</td>
<td>5423</td>
<td>8.63</td>
<td>- 180</td>
</tr>
<tr>
<td>2015</td>
<td>0</td>
<td>4608</td>
<td>8.44</td>
<td>- 190</td>
</tr>
<tr>
<td>2020</td>
<td>0</td>
<td>3783</td>
<td>8.44</td>
<td>-</td>
</tr>
</tbody>
</table>

The optimal pumping was found out through bisection method. The constraints are piezometric heads which should lie between 0.5 and 1.0 m. This range is selected on the idea that maintaining piezometric pressure above mean sea level reduces or arrests seawater intrusion. The deviation from these constraints are penalised. Therefore, the objective is to minimise the penalties. Penalties are calculated for various percentage reductions in pumping. Penalties for zero and 100 percent reduction in pumping are 2781 and 6894 respectively. The bisection trials were carried out in between zero percent and hundred percent reduction in pumping. Penalties for various reductions in pumping were arrived at. Figure 8.1 shows the change in penalty with reduction in irrigation demand.
Fig. 8.1 Change in penalty with reduction in irrigation demand
Figure 8.2 shows the change in piezometric heads with reduction in pumping. It is quite evident that 28 percent reduction in pumping gives the minimum deviation from the constraints on head, that is, 28 percent reduction in pumping achieves the objective. After finding the optimal percentage reduction in pumping, the same was used in the simulation model to arrive at various results, such as head and concentration contours, water and salt balance and temporal variations of head and concentration as shown below.

i. The minimum piezometric head is improved by +8 m (Table 8.1) in the first nine years and the same was continued (Figure 8.3).

ii. Similarly, the reduction in concentration was steep in first nine years from 8329 mg/l in 1996 and then it reduces slowly and it reaches to 3783 mg/l at 6.5 km in 2020 (Table 8.1).

iii. The 1000 mg/l isochlor nearly at 10 km in 1996 retreats back to 8.5 km in 2020 from the coast. Hence, the 1000 mg/l isochlor front moves back by 1500 m (Figure 8.4).

iv. If the pumping is cut down by 28 percent per year, there is an outflow of 120 mcm of either fresh groundwater or diluted seawater which washes out 0.95 million kilogram of salt in 24 years through sea boundary. When the zero percent reduction in pumping is compared with scenario 6, the condition was reverse. It provides 131 mcm of saltwater that brings 4.5 million kilogram of salt in 24 years into the aquifer.

v. Figure 8.5 shows the three dimensional view of the level of concentration in the years 2005, 2010, 2015 and 2020. The three dimensional figures (Figure 8.5) clearly indicates the position and subsequent retreat of 1000 mg/l isochlor front with reference to 1996.
Fig. 8.2 Change in piezometric head with reduction in irrigation demand
Fig. 8.3 Projected piezometric head contours for scenario 6
Fig. 8.4 Projected isochlors at intervals of 1000 mg/l for scenario 6
Fig. 8.5  Comparison of the projected three dimensional frontal movement for the scenario 6 for the years 2005, 2010, 2015 and 2020
8.3.2 Scenario 7: Optimal Recharge and Location

The objective is to minimise the sum of temporal and spatial artificial recharge fluxes for a period of ten years. The purpose of this model is to minimise the total amount of recharge to the aquifer in order to reclaim the seawater intruded aquifer.

i. The objective is to find the optimal (minimum) recharge rate to reclaim the polluted aquifer.

ii. Even though a 24 year time horizon is considered, only for last ten years, the values of head, concentration and recharge are used in the optimality check. Due to the imposed artificial recharge, the aquifer system may be in a disturbed condition in the initial years and hence the first fourteen years data on head, concentration and recharge are not considered in the optimality check.

iii. One year is taken as a cycle. The recharge pattern between cycles is kept constant. Each annual cycle is divided into four stress periods based on rainfall pattern. The four distinct seasons are (i) January to May, (ii) June to September, (iii) October and November and (iv) December.

Division of a year into four stress periods leads to four decision variables and the other decision variable is the total recharge. The first four decision variables denote the sharing of the total recharge while the fifth decision variable is the total recharge itself. Thus this becomes a six dimensional problem in which the sixth axis is the penalty axis. The recharge in each stress period is distributed among 20 cells of the discretised aquifer. The simulation model uses all the aquifer parameters and boundary conditions that are finalised after calibration and testing of
the aquifer. In this scenario, the optimal recharge is found without adjusting the 1996 pumping pattern.

The objective function which constitutes the unconstrained minimisation problem for the proposed management model can be expressed as

\[
\text{minimise } \Sigma \text{ph} \cdot \text{dh} + \Sigma \text{pc} \cdot \text{dc} + \Sigma \text{pr} \cdot \text{dr} \quad \forall \ i,j,k
\]  \hspace{1cm} (8.9)

8.3.2.1 Penalty values

The piezometric head \( h_{ij} \) is constrained in the range of 0.5 to 1 m, since the piezometric head above the mean sea level prevents the sea water intrusion. The penalty for the deviation from this range is taken as follows.

<table>
<thead>
<tr>
<th>Head ( h ) (m)</th>
<th>Penalty (ph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h &lt; 0.5 )</td>
<td>((0.5-h) \times 10)</td>
</tr>
<tr>
<td>( 0.5 \leq h \leq 1.0 )</td>
<td>0</td>
</tr>
<tr>
<td>( h &gt; 1.0 )</td>
<td>((h-1.0) \times 10)</td>
</tr>
</tbody>
</table>

The recharge quantity is constrained to be less than 20 mcm/year. This has been decided based on the available water at the recharge zone. The penalty for the deviation from the specified range of recharge is taken as follows.

<table>
<thead>
<tr>
<th>Recharge ( R ) (mcm/Year)</th>
<th>Penalty (pr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R \leq 20 )</td>
<td>0</td>
</tr>
<tr>
<td>( R &gt; 20 )</td>
<td>10000</td>
</tr>
</tbody>
</table>
The temporal and spatial distribution of pollutant concentration in the aquifer should not fall below the specified value (usually zero) and these concentrations should not exceed the specified threshold values to meet the water quality standards for the intended use. The penalty for concentration is fixed as follows.

<table>
<thead>
<tr>
<th>Concentration C (mg/l)</th>
<th>Penalty (pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C ≤ 1000</td>
<td>0</td>
</tr>
<tr>
<td>C &gt; 1000</td>
<td>(C - 1000) * 1</td>
</tr>
</tbody>
</table>

The nonlinear optimisation problem was solved with HJ method combined with groundwater flow model and the solute transport model. To represent the behaviour of the groundwater flow and chloride concentration in the management model, flow and solute transport models were linked explicitly to the optimisation program as a subroutines (Figure 8.6). Flow and transport models are called repeatedly by HJ model. HJ model determines the recharge rates. These recharge rates are passed to flow and solute transport model and progresses towards an optimal point by comparing heads and concentrations with the previous point. This procedure will be continued until optimum point is determined that minimises the objective.

Approximately 90 to 135 calls to flow and solute transport were required to find the optimal points. Each run of the flow and solute transport model required about 70 minutes of Central Processing Unit (CPU) time on a Pentium AT 586 personal computer with 100 MHz speed. Though the system behaves linearly, emphasis should be placed on the fact that a large number of calls to flow and transport model are required to obtain an optimal solution. Although the number of calls to simulation model may be large, the optimisation technique provides an efficient way to identify optimal recharge strategies, given the large number of decision variables.
Optimisation Starts

Initialise decision variables with arbitrary values (recharge variables)

Call Simulation Model
Simulate Flow and Solute Transport
Solve for Head and Concentration

Pickout Head and Concentration (State Variables) from the simulated results and find the value of objective function (F). Let optimal = F

Pattern Search Loop Starts

Direction Search Loop Starts

Select decision variable and change the value of it by increasing/decreasing by delta and keep the other variables same

Find the values of objective function at the new points (F1 and F2).

If F1 < Optimal

Yes

Optimal = F1

No

Fig. 8.6 Flow chart for the combined simulation-optimisation model
After a cycle of processing all variables, find the improvement (d) between the start and end of the cycle.

Move in the same direction by multiplying the improvement (d) with an acceleration factor (u). This is a new starting point for the next cycle.

Continue Pattern Search Loop

Continue till convergence

Fig. 8.6 Flow chart for the combined simulation - optimisation model (continued)
8.3.2.2 Location analysis

After finding the optimal total recharge quantity and its distribution, optimal location analysis was carried out. In this aquifer system, two troughs in piezometric surface, one at 6.5 km and the other at 13.5 km from the coast are existing. It is obvious that through control of these troughs, it is possible to control seawater intrusion. The optimal location for recharge was searched between 3.0 and 13.0 km from the coast by using bisectional search method. Figure 8.7 shows the variations of penalty at various locations.

8.3.2.3 Results of scenario 7

The total recharge was initially distributed equally to all the stress periods. About 20 starting points are considered and for each starting point, a best point (local optimal point) is obtained. All the 20 starting points led to the same optimal point. The results are shown in the following Table 8.2. Optimal recharge quantity of 8.1 mcm/year and optimal location at 6.5 km from the seacoast were arrived through this analysis.

Table 8.2  Input parameters and penalty

<table>
<thead>
<tr>
<th>Starting Point No.</th>
<th>Total Recharge mcm/year</th>
<th>Recharge distribution (percentage)</th>
<th>Penalty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Period 1</td>
<td>Period 2</td>
</tr>
<tr>
<td>1</td>
<td>8.1</td>
<td>25.0</td>
<td>15.0</td>
</tr>
<tr>
<td>2</td>
<td>8.1</td>
<td>70.0</td>
<td>20.0</td>
</tr>
<tr>
<td>3</td>
<td>6.4</td>
<td>63.6</td>
<td>27.1</td>
</tr>
<tr>
<td>4</td>
<td>4.8</td>
<td>70.6</td>
<td>27.1</td>
</tr>
<tr>
<td>5</td>
<td>3.0</td>
<td>67.6</td>
<td>28.8</td>
</tr>
<tr>
<td>6</td>
<td>1.6</td>
<td>40.9</td>
<td>52.5</td>
</tr>
<tr>
<td>Optimal Point</td>
<td>8.1</td>
<td>58.5</td>
<td>26.8</td>
</tr>
</tbody>
</table>
Fig. 8.7 Variations of penalty with recharge locations
The optimal recharge quantity and its distribution at optimal location was fed into the simulation model to arrive at the various detailed results from which head and concentration contours, isochlor front movement and variations of heads and concentration were drawn. The summarised results of the scenario 7 are shown in the Table 8.3.

### Table 8.3 Summary of results for scenario 7

<table>
<thead>
<tr>
<th>Year</th>
<th>Minimum head (m)</th>
<th>Concentration at 6.5 km (mg/l)</th>
<th>Position of 1000 mg/l isochlor (km)</th>
<th>Distance moved by 1000 mg/l isochlor (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>-8.0</td>
<td>8329</td>
<td>9.95</td>
<td>-</td>
</tr>
<tr>
<td>2005</td>
<td>-7.27</td>
<td>2264</td>
<td>9.84</td>
<td>-110</td>
</tr>
<tr>
<td>2010</td>
<td>-4.63</td>
<td>1358</td>
<td>6.94</td>
<td>-2900</td>
</tr>
<tr>
<td>2015</td>
<td>-5.27</td>
<td>716</td>
<td>6.75</td>
<td>-190</td>
</tr>
<tr>
<td>2020</td>
<td>-4.65</td>
<td>502</td>
<td>6.56</td>
<td>-190</td>
</tr>
</tbody>
</table>

i. The minimum piezometric head improves steadily from -8.0 m to -4.65 m during the period 1996 to 2020 due to artificial recharge as shown in Figures 8.8.

ii. The reduction in concentration is very steep in the first ten years from 8329 to 2264 mg/l and then it reduces steadily to 502 mg/l as shown in Table 8.3.

iii. The 1000 mg/l isochlor front occupies 9.84 km in 2005 with a slight retrieval of the front as it moves back to 6.94 km in 2020. There is a large retrieval of the front in these five years and then it moved back slowly. On the whole the isochlor moved back by 3390 m in 24 years as shown in Figure 8.9.
Fig. 8.8  Projected piezometric head contours for scenario 7
Fig. 8.9  Projected isochlors at an intervals of 1000 mg/l for scenario 7
iv. For the 8.1 mcm/year of artificial recharge it was able to wash out half million kilogram of salt through the outflow of diluted seawater quantity of 62 mcm.

v. Figure 8.10 shows the three dimensional view of concentration levels in the years 2005, 2020, 2015 and 2020. Since the recharge is at 6.5 km, there is more reduction in concentration in the central zone.

vi. Figures 8.11a to 8.14a indicate that the piezometric head fluctuates steadily. The rate of improvement in the piezometric head for the scenario 6 is better than the scenario 7, because the pumping is cut down throughout the aquifer system.

vii. Figures 8.11b to 8.14b indicate the variations in the chloride concentration at various locations. In all locations the reduction concentration is more in scenario 6 compared to the scenario 7 except at location 11526. As the recharge is at 6.5 km near the well 11526, the clean up is more in scenario 7 compared to scenario 6.

8.4 CONCLUSIONS

From the scenario 6 and 7, it is evident that the aquifer is not reclaimed completely. It is not possible to reclaim the aquifer within a short time horizon. It will take much longer time. Always the piezometric head reaches steady state quickly whereas the salt concentration will be always in transient condition because of dispersion and diffusion. When the scenarios 6 and 7 are compared, the reduction in pumping takes away more salt from the system than the artificial recharge. The 28 percent reduction in pumping reduces irrigation pumping by 10.4 mcm/year. This reduction in pumping takes away more salt than the 8.1 mcm/year recharge washout.
Fig. 8.10 Comparison of the projected three dimensional frontal movement for the scenario 7 for the years 2005, 2010, 2015 and 2020
Fig. 8.11a Fluctuations of the piezometric head for scenarios 6 and 7 at the well 11526

Fig. 8.11b Variations of projected chloride ion concentration for scenarios 6 and 7 at the well 11526
Fig. 8.12a Fluctuations of projected head for Scenarios 6 and 7 at the well 11529

Fig. 8.12b Variations of projected chloride ion concentration for Scenarios 6 and 7 at the well 11529
Fig. 8.13a Fluctuations of projected head for Scenarios 6 and 7 at the well PW 17

Fig. 8.13b Variations of projected chloride ion concentration for Scenarios 6 and 7 at the well PW 17
Fig. 8.14a Fluctuations of projected head for Scenarios 6 and 7 at the well PW 32

Fig. 8.14b Variations of projected chloride ion concentration for Scenarios 6 and 7 at the well PW 32
Artificial recharge is expensive. Hence reduction in pumping is suggested. To safeguard the aquifer from further intrusion, it is essential to reduce the pumping. This is possible either by changing the agricultural pattern or buying the groundwater rights from the farmers. Then the question regarding farmers employment arise. It is possible, that they can be employed under special category. Buying the groundwater rights may lead to unemployment problems, which must be solved with alternate arrangements to them.