CHAPTER 8

GROUNDWATER FLOW AND SOLUTE TRANSPORT MODELLING

8.1 GENERAL

In order to understand the Salinisation processes and the time that it might take to flush tsunami-induced Salinisation, a regional solute transport model was developed for this region in order to simulate the groundwater head and chloride concentration. The regional model was developed using the commercial software known as FEFLOW as explained in Chapter 3. In this chapter, the various stages involved in the development of the regional flow model, input parameters required for this model and the results obtained from the model are presented. The data obtained through geophysical, geohydrological and geochemical studies were used as input parameters for the model. Initially, the flow model was developed and, after obtaining satisfactory results, chloride ion simulation was carried out to study the effect of tsunami in the inundated region of the Kalpakkam coastal aquifer. The model was then used to predict the time period likely to lapse for flushing out the tsunami-induced salinity.

8.2 MODEL CONCEPTUALIZATION

Model conceptualization is a set of assumptions and hypothesis that facilitate the quantification process. The model was conceptualized with the help of detailed study of geological and geoelectrical data, and water level
fluctuations in the wells of the study area. Groundwater occurs in this area in the Quaternary unconsolidated sediment formations. All the wells located in this area penetrate only these sediments (sand and sandy clay). Hence, this aquifer was conceptualized as an unconfined, single-layered system. Even though the aquifer is likely to extend below this formation up to the weathered or fractured hard rock formation, it was assumed that the occurrence of groundwater in this zone is not significant. Subsequently, for this model concept, the estimation of different model parameters was carried out.

8.2.1 Model Grid and Boundary Conditions

The aerial extent of the model and boundary conditions were derived from the hydrogeological conditions of the area. The area chosen for Modelling has the Bay of Bengal to its east, Buckingham Canal on its west, and backwaters to the south. These boundaries can be very well assumed as constant head boundaries as the water levels in the water bodies are generally at mean sea level throughout the year. The northern boundary of the model area was fixed arbitrarily, as no investigation could be carried out in this area due to the location of the Indira Gandhi Center for Atomic Research (IGCAR). Hence, this boundary was considered as a variable head boundary as this region has Quaternary sediment deposit of about 15 m in thickness. A map of this study area with these boundaries was geographically registered and imported as a shape file. Boundaries of the map were digitized as polygons using polygon tool of the FEFLOW software. This digitized map was used to automatically generate triangular grid pattern. Thus, the study area was discretized in to 720 nodes with 639 elements encomposing a total area of approximately 2 km² (Figure 8.1).
8.2.2 Input Parameters

The model was developed by incorporating geologic data, geoelectrical data, measured and inferred hydrologic data. The data required for Modelling can be broadly divided in two sets, as data related to physical framework and hydrological data (Table 8.1).

Figure 8.1 Boundary conditions and discretisation of the study area
Table 8.1 Data required for developing a numerical model

<table>
<thead>
<tr>
<th>Physical framework</th>
<th>Hydrological stresses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquifer geometry</td>
<td>Groundwater abstraction and recharge</td>
</tr>
<tr>
<td>Type of aquifer</td>
<td>Solute concentration</td>
</tr>
<tr>
<td>Aquifer thickness and lateral extent</td>
<td>Aquifer stress</td>
</tr>
<tr>
<td>Aquifer characteristics</td>
<td></td>
</tr>
</tbody>
</table>

8.2.1.1 Aquifer Geometry

The aquifer geometry includes the elevations of the top and bottom of an aquifer. The elevation of the ground surface was initially estimated by field survey using Total Station Sokia 610. The depths to the top and bottom of the aquifer were derived from geoelectrical data, well logs and water levels. These values were extrapolated for the entire area considering the lithological variations and field study of well sections. The elevation of aquifer ranges between 0.5 and 6.5 m above mean sea level. The elevation of bottom ranges between 8 and 14 m below mean sea level, and increases towards east. The top and bottom elevations of the aquifer used for Modelling are shown in Figure 8.2.

8.2.2.2 Aquifer Parameters

Aquifer parameters, which include porosity, hydraulic conductivity and specific yield, were assigned to each cell based on the data obtained from the Central Ground Water Board (CGWB) and are listed in Table 8.2. Specific yield of 0.22 was uniformly assumed for the area. A hydraulic conductivity of 32-45 m/day was assigned in the sandy areas, while 27-32 m/day was assumed in areas where sand with clay was present. The
longitudinal and transverse dispersivity values were used based on the values given in literature (Freeze and Cherry 1979) for the geological formations of this area.

Figure 8.2 Elevations of aquifer top and bottom
Table 8.2 Aquifer parameters used in the model

<table>
<thead>
<tr>
<th>Aquifer parameters</th>
<th>Quaternary sediments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>0.17-0.25</td>
</tr>
<tr>
<td>Specific yield ( (S_y) )</td>
<td>0.1-0.27</td>
</tr>
<tr>
<td>Horizontal hydraulic conductivity ( (K_h) ) m/day</td>
<td>27-45</td>
</tr>
<tr>
<td>Vertical hydraulic conductivity ( (K_h) ) m/day</td>
<td>12-18</td>
</tr>
<tr>
<td>Longitudinal dispersivity ( a_L ) (m)</td>
<td>5-12.5</td>
</tr>
<tr>
<td>Transverse dispersivity ( a_T ) (m)</td>
<td>0.5-1.2</td>
</tr>
</tbody>
</table>

8.2.2.3 Groundwater abstraction

The groundwater of the study area is abstracted mainly for domestic and, to a certain extent, for irrigation purposes. About 0.5 MGD is abstracted for domestic, while 0.3 MGD is abstracted for agriculture purposes (CGWB 2001). This abstraction is distributed over the study area based on land use patterns.

8.2.2.4 Groundwater recharge

The monthly recharge rate assigned to the model area. The study of the long-term relation between rainfall and water level was made in order to understand the recharge process. This assisted in the calculation of the recharge rate, and it was found that only when the monthly rainfall exceeds 100 mm, rainwater infiltrates into the groundwater system. That is, the groundwater level in the wells rises only when the rainfall is >100 mm. When
the monthly rainfall was from 100 to 200 mm, 45% of it was assumed as recharge. When the monthly rainfall was greater than 300 mm, a recharge value of 50% was assumed. For the areas were near the Buckingham Canal, recharge was considered to vary between 25 and 35% due to the presence of sandy clay in these regions.

8.2.2.5 Initial groundwater head

The groundwater head data obtained from the monitoring wells during December 2004 was taken as the initial groundwater head. The head ranges from between 1.5 and 3.4 m above MSL. Potentiometric surface of the unconfined aquifer during this month is given in Figure 8.3.

8.2.2.6 Initial solute concentration

The initial chloride concentration used as input to the model ranged between 15 and 480 mg/l in the non-inundated region. In the inundated region, the initial concentration was considered as 19,000 mg/l when the tsunami hit the coastal zone of Kalpakkam region. In the Bay of Bengal, the concentration of chloride is about 19,000 mg/l; the concentration of sea water was, therefore, considered as the initial chloride concentration in the inundated region.
Figure 8.3 Initial groundwater head
8.3 MODEL CALIBRATION

Calibration of the groundwater flow model was carried out with a number of trial runs to achieve agreement between the simulated and the observed heads. In other words, calibration is the process of parameter estimation conditioned on head measurements. The density variation between the fresh and sea water was considered in the model simulation. For fresh water, the density was considered as 1 and, for sea water, it was considered as 1.025. Minimizing the difference between the computed and the field water heads and chloride ion for all observation points was done during calibration.

8.3.1 Steady State Calibration

The aquifer condition of December 2004 was taken as the initial condition for the steady state model calibration. Off all the input parameters, the hydraulic conductivity values was the only poorly-known one, as only one pumping test had been carried out in this area. During calibration, the hydraulic conductivity values alone were modified between 45 and 65 m/day. Based on lithological variations, it was decided to vary hydraulic conductivity values up to 10% of the pumping test results in order to get a good match of the computed and observed heads.

8.3.2 Transient State Calibration

The hydraulic conductivity values arrived at from the steady state calibration and the other initial input parameters were then used as the initial condition in the transient model calibration. The specific yield distribution, time variable recharge and pumping distribution were assigned to the transient model. The transient calibration was carried out for the time period of 2 years from January 2005 to January 2007, with the initial water table condition of
January 2005. The model was calibrated for 25 stress periods, from January 2005 to January 2007 using 30 day time steps under transient conditions.

Calibration of transient model was achieved by number of trials until a good match between computed and observed heads over space and time was obtained by varying the specific yield, hydraulic conductivity and recharge values within the permissible limits. Model calibration redefined estimates of the hydrologic characteristics until the model behavior matched with the historic data. The specific yield values were decreased by 5% in comparison with the field values. Thus, during model calibration, the specific yield and hydraulic conductivity (K) values were effectively varied so as to obtain good match between the observed and simulated heads. The initial input parameters and the modified values of K and specific yield after calibration are presented in Table 8.3.

Calibration of the hydraulic head was continued for chloride ion simulation. Hydrological stress like pumping, recharge and aerial salinity distribution was assigned to every grid. Chloride concentration does not affect the flow field significantly. After the flow simulation was complete, the transport model retrieved the stored hydraulic heads for further computations. Once the initial simulation was over, the chloride concentrations in the model were adjusted within their permissible limits to obtain better results that corresponded with the computed and measured concentrations.
Table 8.3 Initial and calibrated hydraulic parameters

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Geology of the area</th>
<th>Hydraulic conductivity (m/day)</th>
<th>Specific yield</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Initial</td>
<td>Calibrated</td>
<td>Initial</td>
</tr>
<tr>
<td>1</td>
<td>Sand</td>
<td>45</td>
<td>55</td>
<td>0.27</td>
</tr>
<tr>
<td>2</td>
<td>Sandy clay</td>
<td>25</td>
<td>30</td>
<td>0.10</td>
</tr>
</tbody>
</table>

8.4 MODEL SIMULATION

After successful calibration, simulation was carried out to estimate the groundwater head and chloride concentration during the tsunami event.

8.4.1 Groundwater Head

After calibration, the final run was conducted for 25 stress periods using 30 day time steps. The computed groundwater heads over space and time of this period were compared with the observed data. Both observed and computed groundwater heads were closer to each other with a minimum and maximum difference of 0.2 and 0.5 m, respectively. At well no 3, however, a difference of 0.8 m was observed between the field and simulated heads. This may be attributed to the deficiency in pumping data. The spatial distributions of the simulated and observed groundwater heads are similar to each other. A difference of 0.5 to 1.0 m between the measured and computed groundwater heads occurred at places of higher water table elevation; this might be due to variations in topographical elevation over short distances. The pattern and shape of the simulated groundwater head differed from pre to post monsoon period. In general, the simulated regional groundwater head over space and time followed similar trend of observed head, representative of the actual field conditions.
A study of the simulated potentiometric surface of the aquifer indicated that the highest heads were found in the central part of the study area, which is a general reflection of the topography. The simulated regional heads for August 2005 and January 2006 are shown in Figure 8.4. The computed groundwater heads of wells 4, 7 and 12 of the study area (Figure 8.5) mimic the observed values. In general, the simulated results indicate that this aquifer system is stable under the present pumping rate. The regional groundwater flow direction is from central part to the eastern and western directions. The simulated groundwater flow vectors are shown in Figure 8.6.

**8.4.2 Solute Transport Modelling**

Many contemporary groundwater problems include the investigation of flow and transport of contaminants. In order to investigate the effects of tsunami that hit the coastal zone of Kalpakkam region on December 26 2004, the simulation of solute was carried out. Even though concentration of all major ions was monitored it was decided to consider the transport of chloride only for modelling. As the chloride is the most dominant in the seawater and it is also a conservative ion, transport this ion was taken into account in this modelling study. Initially, the simulation was carried out for a period of 6 days, i.e. from December 26 to December 31, 2004, using 144 stress periods each having 1-hour time steps in order to understand the effect of tsunami at closer intervals of time. At 9.30 am on December 26, 2004, the solute concentration was introduced by a saline water head to simulate the tsunami waves, and the model was run up to December 31, 2004. The concentration of solutes at the end of 144th stress period was considered as input for the subsequent model run that was carried out for a period of 26 months i.e. January 2005 – February 2007. This run was carried out using 26 stress periods, each having 30 day time steps. The method of characteristics
technique was used for solving the simulation for solute transport because of its effectiveness in handling the advection–dispersion problems.

Figure 8.4  Simulated groundwater head for August 2005 and January 2006
Figure 8.5 Comparison of simulated and observed groundwater heads
Figure 8.6 Regional groundwater flow vector of the study area
Simulation of the concentration of chloride for the months of January 2005 through January 2007 was carried out. The chloride concentrations of January 2005 and January 2007 are shown in Figures 8.7 and 8.8, respectively. The computed and observed solute concentration of wells 1, 2, 8, 9, 11, 12 are shown in Figures 8.9 and 8.10. Simulated chloride concentrations reasonably match with the observed trends. There is gradual decrease in the concentration of chloride up to the month of July 2005; there is also a raise in the concentration in the months of August and September 2005. There was a gradual decrease in the solute concentration of chloride after the successive monsoon seasons. But at end of the 26 stress period, the chloride concentration was more along the southeastern boundary of the study area.

8.5 SENSITIVITY ANALYSIS

Sensitivity analysis is used as means of identifying the mechanisms and input parameters that have greater influence on the output for both historical and predictive simulations. The process of model development and sensitivity analysis allows having better understanding of the response of systems to changing hydrologic parameters. Sensitivity analysis was used during the model calibration to refine initial estimates of input parameters, and after the model calibration, to determine the parameter which had the largest effect on simulated head values. The model is considered to be sensitive to an input parameter when small changes in the values of the parameter result in large changes in simulated head values.
Figure 8.7  Simulated chloride ion concentration of groundwater in January 2005
Figure 8.8  Simulated chloride ion concentration of groundwater in January 2007
Figure 8.9  Computed and observed chloride concentration in well no 1, 2 and 8
Figure 8.10  Computed and observed chloride concentration in well no 9, 11 and 12
8.5.1 Hydraulic Conductivity

Several runs are performed to allow for the sensitivity (interval) analysis of calibrated model parameters that are not supported by any measurements. Sensitive analysis was tested by varying the hydraulic conductivity up to 10% uniformly, and the response of the model was monitored. The model run with an increase and decrease of 10% K values showed highly negligible change in groundwater head values. It was noted that the groundwater head decreased by a negligible fraction of 0.1-0.5 m, with a maximum increase of 10% (Figure 8.11). This analysis clearly indicates that any increase or reduction of hydraulic conductivity values, at least up to 10%, would not drastically alter the groundwater head values.

8.6 MODEL FORECAST

The model developed for the Kalpakamm coastal aquifer was used to predict the response of the aquifer system to the anticipated changes in the hydrological stresses. The aquifer response for different input and output fluxes was studied in order to understand behavior of this aquifer system. The model forecast was carried out until January 2008.
Figure 8.11 Sensitivity of the model for changes in hydraulic conductivity
8.6.1 Normal Rainfall Condition

The model was run to predict the regional groundwater head in this area until the year 2008. For these runs, the monthly average rainfall calculated from 70 years rainfall data was used. The present level of groundwater abstraction was considered for this simulation. There is not much increase or decrease in water level. The predicted groundwater head until February 2008 is shown in Figure 8.12. The solute concentration of chloride in the southeastern part has decreased to the normal level after the monsoon of 2007. The predicted solute concentration until Jan 2008 was shown in (Figure 8.13). The model forecast indicates that tsunami-induced salinity in this aquifer system would be flushed out with normal annual rainfall by February 2008. Thus, solute transport Modelling carried out using this finite element model helped to understand the process of Salinisation, and remediation of the aquifer by natural recharge.
Figure 8.12 Predicted groundwater head until February 2008
Figure 8.13  Predicted chloride ion concentration in January 2008