THREE DIMENSIONAL FINITE ELEMENT MODELLING OF GROUNDWATER FLOW FOR SUSTAINABLE PUMPING FROM NORTH OF CHENNAI COASTAL AQUIFER, TAMIL NADU, INDIA

S.P.Rajaveni¹, Indu S. Nair² and L.Elango³

Groundwater flow modelling is an important tool to study the behavior of an aquifer system and quantitative prediction of response of that system under varies hydrological stresses. Several studies have been carried out on numerical groundwater flow modelling by finite difference methods (Chao et al. 2010, Senthilkumar and Elango, 2004) and finite element methods (Balazova et al. 2002) for effective groundwater management. The objective of this study is to assess the optimum pumping strategy for sustainable management of groundwater resources in alluvial aquifers north of Chennai by three dimensional finite element groundwater flow model. The aquifer of this area is conceptualized into three layered system with a unconfined aquifer at the top, aquitard at the middle and a semi-confined aquifer at the bottom. The semi-confined aquifer is underlined by impervious clay formation. Hydraulic conductivity and specific yield of the aquifers were obtained from the pumping tests carried out by UNDP (1987). About 10 to 17 % of rainfall was considered as groundwater recharge. Groundwater abstraction for irrigation was estimated from the crop water requirement. Steady state calibration was made with the initial groundwater level of March 1988. This calibration helped to fine-tune the assumed hydraulic conductivity and specific yield values. The calibrated finite element model was used to simulate groundwater head under transient condition for time period of 15 years during 1988 to 2002. Fig.1 shows steady state and transient state calibration results of observed and simulated groundwater head. The time series analysis of the simulated and observed groundwater head in top aquifer (Well No.1) is shown in Fig. 2. Further, the model was validated using the observed groundwater head for the period of April 2002 to March 2010. There is reasonable level of similarity between the observed and simulated groundwater head. Groundwater model developed will be helpful for sustainable managing of groundwater resources and also it can be useful for the planning and management tool.

Fig. 1. (a) Steady state calibration for top aquifer (b) Steady state calibration for bottom aquifer
**Fig. 2. Variation in observed and simulated groundwater head in a well in top aquifer**

**REFERENCES**


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THREE DIMENSIONAL FINITE ELEMENT MODELLING OF GROUNDWATER FLOW FOR SUSTAINABLE PUMPING FROM NORTH OF CHENNAI COASTAL AQUIFER, TAMIL NADU, INDIA

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Abstract: Groundwater from the coastal aquifers north of Chennai is being pumped since 1981 to meet the increasing demand. Huge groundwater extracting in the coastal aquifers groundwater causes lowering of groundwater table which led to seawater intrusion. The objective of this study is to assess the behavior of this aquifer to seawater intrusion under different hydrological stresses by groundwater modelling. Intensive field visits were carried out and 45 monitoring wells were identified. Groundwater level has been measuring once in two months from the year 2011. Aquifer properties such as transmissivity and specific yield were obtained from other agencies. Finite element groundwater flow modeling was carried out using FEFLOW with the period of March 1988 groundwater head as an initial condition. Boundary conditions are assigned based on the groundwater flow across the study area. Steady state calibration was done to adjust the hydraulic conductivity and specific yield values. Time varying inputs such as abstraction and recharge were used and calibration of the model was made during the period from 1988 to 2002. Validation of the model was made for comparing the simulated and observed groundwater levels from the year 2003 to 2012. Simulated groundwater level was in near agreement with observed groundwater level. The model was later used to assess the variation in groundwater levels with changes in recharge and pumping rates. This study was useful for understanding the response of subsurface aquifer system under different hydrological stresses and sustainable utilization of groundwater.

Keywords: Coastal aquifer; numerical modelling; FEFLOW; groundwater flow.

INTRODUCTION
Groundwater flow modelling is an important tool to study various hydrogeological processes such as estimating the aquifer properties, behavior of real aquifer system and quantitative prediction of response of that system by applying various stress conditions. Three dimensional groundwater flow models are effective groundwater management tool to assess the sustainability of aquifer system. Several studies have been carried out by numerical groundwater flow modelling of finite difference (Ayenew et al. 2008, Chao et al. 2010, Elango 2005, Senthilkumar and Elango, 2004) and finite element method (Balazova et al. 2002) for effective groundwater management.

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Barazzuoli et al (2008) developed a three dimensional finite element model to determine the most important components of the water budget and to identify the relationship between river, aquifer and sea. The present study was carried out in north of Chennai coastal aquifer which is extensively being used for irrigation, industry and Chennai municipal water supply. The main objective of this study is to develop a three dimensional groundwater flow model which will be helpful for managing the aquifer from seawater intrusion.

DESCRIPTION OF THE STUDY AREA

The present study is carried out in a part of Arani-Kortatalaiyar (A_K) river basin which is located around 40 km north of Chennai metropolitan city (Fig. 1) and covers an area of about 603 km². Arani and Koratalaiyar are the two non-perennial rivers present in this area and it flows for about three months in a year during rainy season. Eastern boundary is bounded by Bay of Bengal. Topographically, the elevation varies from 0.64 m (Chennai mean sea level, Tide table, 1997) in eastern side to 20 m msl in western side as observed in Survey of India toposheet. This area experiences arid to semi-arid climate with hot climate during the summer (April-June) having a temperature ranging from 34.7°C to 37.5°C and in winter (November - January) the temperature varies between 20.4°C and 22.7°C. The normal annual rainfall in this area varies from 950 mm to 1150 mm falling mostly during the northeast monsoon (October-December). Rice, pulses, groundnut, sesame, sugarcane and vegetables are the major crops cultivated in this area (CGWB, 2007).

![Fig. 1. Location of study area with monitoring wells and rain gauge station](image)

GEOLOGY & HYDROGEOLOGY

Geologically, this area is composed of rocks from Archaean to Recent age. The detailed stratigraphic sequence of geological formation is given in Table 1. Crystalline rocks of
Archaean age comprising gneiss and charnockite forming the basement. Most of this area is exposed by Quaternary deposits, which consists of laterite and alluvium deposit (UNDP, 1987). Alluvium deposits occur along the A-K river courses. The alluvium deposits comprise of sand, silt, sandy clay, gravel and pebbles. Laterite is found in southwest and northwest part of study area and small patches of sandstone and conglomerate are identified in southwestern part (Fig. 2).

![Geological outcrop and subsurface geology of the study area](image)

The thickness and lithological compositions of this area were identified from the bore hole logs collected from Chennai Metro Water Supply and Sewerage Board (CMWSSB) and UNDP (1984) report. Total thickness of alluvial formation found to be about 50 m. Groundwater occur in this area in two aquifer system dividing it into top unconfined aquifer (15 m thick) and the bottom semi-confined aquifer (35 m thick). These two aquifers are separated by a aquitard layer of around 5 m thickness (clay patches). Hydraulic conductivity of top aquifer is ranging from 35 m/day to 100 m/day and specific yield values vary in the range from 0.02 to 0.27 (Domenico and Schwartz, 1998). Hydraulic conductivity of bottom aquifer were obtained from the pumping test conducted by UNDP (1987), it varies from 45 m/day to 250 m/day and specific yield values vary in the range from 0.20 to 0.30. The hydraulic conductivity of bottom aquifer is much more high compared to top aquifer. Hence, the bottom semi confined marks as the major aquifer. The average saturated thickness of top aquifer is 10 m and the thickness of bottom aquifer varies between 15 m to 35 m.

<table>
<thead>
<tr>
<th>Table 1. Stratigraphic sequence of the study area (after UNDP 1987)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quaternary (upto 40 m)</strong></td>
</tr>
<tr>
<td><strong>Tertiary (45 - 50 m)</strong></td>
</tr>
<tr>
<td><strong>Upper Gondwana</strong></td>
</tr>
<tr>
<td><strong>Archean</strong></td>
</tr>
</tbody>
</table>
MODEL FORMULATION AND GRID DESIGN

The aquifer is conceptualized by a three dimensional finite element model using Finite Element subsurface Flow system (FEFLOW) numerical code. The finite element model was conceptualized from a detailed study of geology, subsurface litholog and groundwater level fluctuations in monitoring well. Two separate groundwater head is observed in this aquifer. The well with depth less than 20 m has phreatic level and the bore well with depth greater than 20 m has another groundwater head. Total aquifer thickness is 50 m and is divided into three layers: Top layers (0 – 16 m) were considered as top aquifer and middle 2 (17 – 20 m) layers were taken as aquitard and bottom layer (21 – 50) m were assigned as bottom aquifer. This model covers an area of 603 km² and was discretized into 30,000 triangular finite element. The size of finite elements may vary between 6000 m² (coastal side) to 20,000 m² (western side).

BOUNDARY & INITIAL CONDITIONS

The eastern side of the model area is bounded by Bay of Bengal which is considered as constant head boundary condition. The northern and southern boundaries of this area are watershed boundaries where the groundwater flow from these boundaries is negligible, hence they are considered as no flow boundary. About 2 km from northeastern and southeastern boundary, the area is considered as constant head boundary as this side has back waters from Bay of Bengal (Fig. 3).

Fig. 3. Boundary and initial conditions of the model

INPUT PARAMETERS
Aquifer Characteristics

The aquifer properties of hydraulic conductivity and specific yield, obtained from pumping test results (UNDP, 1987) are used to bottom aquifer. The hydraulic conductivity and specific yield values of top aquifer was assigned each zones from geology(Fig. 2). Very less vertical hydraulic conductivity is assigned for aquitard.
Groundwater Recharge

Rainfall is the principal source of groundwater recharge as compared to irrigation return flow, seepage from river and water storage ponds. There are three rainfall stations named Vallur anicut, Ponneri and Chozhavaram in this area. Based on the rain gauge station the model area is divided by using Theissen polygon method. Further, the Thessien polygon was subdivided into 8 zones based on the surface geology. The distribution of recharge values for each zone is shown in Fig. 4. Percentage of groundwater recharge from rainfall for various geological formations are tabulated in Table 2. Arani and Koratalaiyar rivers flow during the monsoons seasons (October to December); around 1 m depth of surface water is assigned in the rivers. Surface water bodies have water only during the period of monsoon. Since, no actual pond water level is available, recharge from the ponds was estimated by assuming pond water levels of 50 cm above ground level during the months in which the rainfall exceeds 300 mm.

![Groundwater recharge zone of the study area](image)

Table 2 Percentage of groundwater recharge for various geological formations (after, GEC, 1997)

<table>
<thead>
<tr>
<th>Geology</th>
<th>% of Groundwater Recharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beach sand</td>
<td>17%</td>
</tr>
<tr>
<td>Sand and silt</td>
<td>16%</td>
</tr>
<tr>
<td>Clayey sand</td>
<td>15%</td>
</tr>
<tr>
<td>Laterite</td>
<td>10 - 13%</td>
</tr>
</tbody>
</table>
Groundwater Abstraction

Groundwater in this area is abstracted for irrigation, domestic, industrial and municipal water supply. Groundwater abstraction calculated based on crop irrigation requirements was considered to provide reasonably accurate method and also had the advantage of allowing historical and temporal variations of abstraction (Charalambous and Garratt, 2009). More than 80% of the groundwater is being used for agricultural and Chennai municipal water supply. About 61% of the land has been used for agricultural purpose which mainly depends on groundwater except monsoon periods (October to December). Groundwater abstraction for irrigation was estimated from the crop water requirement. Diverse crop types for two different seasons of kharif and rabi were mapped from Linear Imaging Self scanning Sensor III (LISS III) satellite image. Water requirement for different crop types was obtained from the report of Department of Agriculture, Tamil Nadu and used for calculating pumping rate. Groundwater abstraction estimated based on crop types and amount of water required for the crop is 284 MCM/yr. Groundwater requirement for the built-up areas were calculated based on the population of the particular area with per capita demand. The calculated abstraction for domestic purpose is 1.94 MCM/yr. Other than this the bottom aquifer is abstracted for municipal water supply (Fig. 5). Groundwater is abstracted from well-fields located in Minjur, Panjetty and Kanigaipar and supplied to municipal supply which is collected from CMWSSB.

Fig. 5. Groundwater abstraction of the study area

RESULTS AND DISCUSSION
Model Calibration

The model was calibrated in two stages such as steady state condition and a transient condition. Steady state calibration for top and bottom aquifer was carried out to eliminate the difference between the observed and simulated groundwater head. Long term groundwater head for top and bottom aquifer were collected from Public Works Department, Tamil Nadu...
(PWD) and CMWSSB. Groundwater head of 9 monitoring wells for top aquifer and 22 monitoring wells for bottom aquifer during the period of March 1988 were used for steady state simulation. Hydraulic conductivity and specific yield were the most unknown parameter obtained from 13 pumping test conducted by UNDP, 1987. Based on the subsurface lithological variations, the hydraulic conductivity and specific yield values may vary up to 10% from initial assigned values for both top and bottom aquifer and to match the observed and simulated groundwater head (Fig. 6). Transient state calibration for top and bottom aquifer was carried out for a period of 15 years from March 1988 to March 2002 with 30 days time step. Transient state calibration was conducted by trial and error method until best fit curve obtained for observed and simulated groundwater head. Table 3 shows the initial and calibrated hydraulic conductivity values.

![Fig. 6. (a) Steady state calibration for top aquifer (b) Steady state calibration for bottom aquifer](image)

**Table 3 Initial and calibrated aquifer parameters**

<table>
<thead>
<tr>
<th>Geology/Pumping test location of the area</th>
<th>Hydraulic conductivity, K (m/day)</th>
<th>Specific yield, S_y</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
<td>Calibrated</td>
</tr>
<tr>
<td>Beach sand</td>
<td>110</td>
<td>100</td>
</tr>
<tr>
<td>Sand and silt</td>
<td>75</td>
<td>85</td>
</tr>
<tr>
<td>Clayey sand</td>
<td>65</td>
<td>50</td>
</tr>
<tr>
<td>Laterite</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>Clay</td>
<td>0.00005</td>
<td>0.000067</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pumping test location</th>
<th>Hydraulic conductivity, K (m/day)</th>
<th>Specific yield, S_y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kattur</td>
<td>73.32</td>
<td>0.23</td>
</tr>
<tr>
<td>Interface</td>
<td>118</td>
<td>0.3</td>
</tr>
<tr>
<td>NE Minjur</td>
<td>228</td>
<td>0.3</td>
</tr>
<tr>
<td>Duranallur</td>
<td>69</td>
<td>0.2</td>
</tr>
<tr>
<td>Panjetti</td>
<td>118</td>
<td>0.18</td>
</tr>
</tbody>
</table>
Simulation Results

The calibrated finite element model was simulated in transient condition for a time period of 15 years from 1988 to 2002. In most of the wells, the simulated head values matched with the observed groundwater head. The time series of the simulated and observed groundwater head in top aquifer (Well No. 1) are shown in Fig. 7. Regional groundwater flow direction is from west to east towards Bay of Bengal.

![Well No 1](image)

**Fig. 7. Variation in observed and simulated groundwater head in a well in top aquifer**

Model Validation

Validation of the model was made by comparing the simulated and observed groundwater levels from the year 2003 to 2012. Simulated groundwater level was in near agreement with observed groundwater level. Time series of groundwater level in well No 10 is shown in Fig. 7. The model was later used to assess the variation in groundwater level for different recharge and pumping rates. This study thus is useful for understanding the response of subsurface aquifer system under different hydrological stresses and sustainable utilization of groundwater.

CONCLUSIONS

Three dimensional finite element groundwater flow modelling was carried out in a north of Chennai coastal aquifer to understand the groundwater flow. Two aquifers identified in this area from subsurface lithologs. The hydraulic conductivity of bottom aquifer is much more
higher compared to top aquifer. Hence, the bottom semi-confined is the major aquifer. The groundwater model reached a fine match between observed and simulated groundwater head. Groundwater model developed will be helpful for sustainable managing of groundwater resources and also it can be useful for the planning and management tool.

ACKNOWLEDGEMENTS

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