Finite element modelling of a heavily exploited coastal aquifer for assessing the response of groundwater level to the changes in pumping and rainfall variation due to climate change
Rajaveni Sundara Pandian, Indu Sumadevi Nair and Elango Lakshmanan

ABSTRACT
Coastal aquifers are always under threat of seawater intrusion due to over-extraction of groundwater. The objective here is to assess aquifer response to variation in pumping and rainfall recharge due to projected climate change by groundwater modelling in a heavily exploited aquifer. Finite element groundwater flow modelling was carried out from March 1988 to December 2030 using FEFLOW software. Steady state calibration was done to match observed and simulated groundwater head by varying aquifer parameters within the allowable range. Transient state calibration was carried out during the period March 1988 to December 2002. The calibrated model was validated by comparing the simulated and observed groundwater head from January 2003 to December 2012. Groundwater head was predicted for a period until 2030 under eight different scenarios of changes in pumping and rainfall recharge. This prediction indicated that 10% increase of recharge and 10% decrease of pumping causes 3 m and 6 m increase in groundwater head in upper and lower aquifers, respectively, by the end of 2030. Groundwater recharge can be increased by rejuvenation of existing surface water bodies, check dams and construction of proposed check dams. Thus, increase of groundwater recharge and decrease in well field pumping is achievable to restore this heavily exploited coastal aquifer in another 20 years.

Key words | Arani-Korttalaiyar river basin, coastal aquifer, FEFLOW, groundwater flow, over-extraction

INTRODUCTION
Large quantities of groundwater are being pumped from coastal aquifers to meet various human needs. These aquifers are sources of fresh water for more than one billion people living in coastal regions (Ferguson & Gleeson 2012). Population growth, over-extraction of groundwater for agricultural and industrial purposes, climate change and sea level rise are the important factors causing seawater intrusion, degradation of chemical quality of groundwater and land subsidence in coastal aquifers (Barazzuoli et al. 2008). Thus, coastal aquifers are always under threat as over-exploitation leads to seawater intrusion and degradation of groundwater quality. Hence, it is very important to utilize coastal groundwater resources with great caution. Sustainable management of coastal groundwater resources is essential in order to prevent seawater intrusion. The projected change in the rainfall due to climate change will play a greater role in seawater intrusion. Groundwater flow modelling can be used as a management tool to assess the sustainability of aquifer systems and to decide on a safe pumping pattern to avoid seawater intrusion. Several studies have been carried out on groundwater flow modelling in order to understand various issues related to sustainable utilization of groundwater. Chao et al. (2010) identified various measures to be taken for achieving sustainable utilization of
groundwater resources by numerical modelling. Many researchers have analysed groundwater flow dynamics, the need for the improvement of groundwater level monitoring network and identified areas for groundwater exploitation by numerical modelling using finite difference method (Senthilkumar & Elango 2001, 2004; Elango 2005; Yang et al. 2012; Alam & Umar 2013; Jean et al. 2013; Okocha & Atakpo 2013). However, it is difficult to consider complex aquifers with irregular boundaries by the finite difference method of groundwater modelling. Advancement in computational technology and the complexity of aquifer systems have allowed researchers to start using finite element method for groundwater flow modelling. Lavigne et al. (2010) developed a numerical groundwater flow model using finite element method in a quaternary sedimentary aquifer. Barazzuoli et al. (2008) and Garcia et al. (1998) simulated coastal aquifers to determine the important components of the water budget and to identify river, aquifer and sea relationships by using finite element model. These studies indicate that the complex aquifer system can be discretized effectively by finite element approach. Movement of fresh groundwater and saltwater in a coastal aquifer mainly depends on the density variation and pumping of fresh groundwater. Coastal aquifers are vulnerable to the variations in groundwater recharge and change in seaward pumping of groundwater (Werner et al. 2012). Datta et al. (2009) used the finite element based flow and transport model to evaluate the effectiveness of planned pumping strategies to locally control seawater intrusion. The present study was carried out in the coastal aquifer north of Chennai from where groundwater is extensively pumped for irrigation, industrial purposes and for providing the Chennai municipal water supply for the past four decades. Chennai is the fourth largest metropolitan city, it is located on the Coromandel coast of the Bay of Bengal and has the third largest expatriate population in India. As the aquifer in this region is heavily exploited and seawater has intruded into the aquifers over a distance of 13 km (CGWB 2013) from the sea, it is essential to identify options for sustainable management of groundwater resources. Rao et al. (2004) simulated groundwater flow by conceptualizing the region as a single layer and estimated the volume of seawater intrusion with and without check dam. However, this study has not considered the spatial and temporal dynamics of fresh water and salt water. Charalambous & Garratt (2009) studied the recharge and pumping relationship through finite element model in the Arani-Korttalaibury (A-K) river basin by considering this region as a confined aquifer, even though it is a two aquifer system. These studies have not considered the presence of two aquifer systems. As there is interaction between the upper and lower aquifer during pumping, it is crucial to consider both aquifers for modelling. Climate change models for the eastern coast of India projected variation in rainfall from a minimum of 858 ± 10 mm to a maximum of 1,280 ± 16 mm (INCCA 2010). The increased rainfall in the 2030s with respect to the 1970s was estimated to be 2 mm–54 mm, an increase of 0.2% to 4.4%, respectively (INCCA 2010). Groundwater modelling studies carried out earlier have not considered the projected change in rainfall due to climate change. The projected change in rainfall has to be accounted for in modelling to assess aquifer response to pumping and recharge. Hence, the present study was carried out with the objective of developing a finite element three-dimensional groundwater flow model to assess the aquifer response to pumping and rainfall recharge due to the projected climate change, which is necessary to identify options for sustainable management of this aquifer system and to mitigate the problem of seawater intrusion.

DESCRIPTION OF THE STUDY AREA

The present study was carried out in a coastal part of A-K river basin, which is located about 45 km north of Chennai metropolitan city and covers an area of about 554 km² (Figure 1). The eastern side is bounded by the Bay of Bengal, and the northern and southern sides of the study area are watershed boundaries. The western boundary of the area was fixed arbitrarily, which is at a distance of about 30 km from the coast. This area experiences tropical wet and dry climate, having a maximum temperature ranging from 32 to 44 °C during summer (April–June) and minimum temperature ranging from 25 to 30 °C during winter (November–January). This area receives rainfall during the southwest (July–September) and northeast (October–December) monsoons. The normal annual rainfall varies from 1,000 mm to 1,200 mm, about 60% of this falling mostly during the northeast monsoon. Two rain gauge
stations are located within the study area at Vallur anicut and Ponneri (Figure 1). Topographically the area gently slopes towards the east, with the maximum elevation of about 20 m at the western boundary. Arani and Korttalaiyar are non-perennial rivers, which flow only for a few days in the year during monsoon rains. However, during the rest of the time the rivers have saline backwaters up to 5 km from the sea. A dendritic to subdendritic drainage pattern was identified in this area (Figure 1). Three well fields are located in the alluvial deposits of paleo channels (Suganthi et al. 2013) and the groundwater is pumped from many wells to meet a part of Chennai city’s water requirement. Agriculture is the major activity in this area and the major crops cultivated are rice, pulses, groundnut, sesame, sugar-cane and vegetables.

MATERIALS AND METHODS

Model description

Groundwater modelling was carried out by the finite element approach. For this purpose, FEFLOW code was chosen as this model is flexible and able to consider the complex geometry of the region. This code solves the groundwater flow equations by numerical approximations using finite element method. FEFLOW is an interactive finite element simulation system for two- and three-dimensional, i.e., horizontal, vertical or axi-symmetric, steady or transient state, fluid density, coupled flow and mass in groundwater system (FEFLOW 6.1 2012). The major stages involved in modelling are: (1) discretization of model area; (2) three-dimensional layer configurations to separate the aquifer system into a number of slices; and (3) problem settings to define the model conditions, simulation time and error tolerance values required for simulation.

RESULTS AND DISCUSSION

Geology

Geologically the area is composed of rocks from Archaean to Quaternary age. Table 1 shows the detailed stratigraphic sequence of geological formations. A geological map from the Geological Survey of India in 1:50,000 scale was updated.

| Table 1 | Stratigraphic sequence of the study area (after UNDP 1987) |
| Quaternary | Fine to coarse sand, gravel, laterite, clay and sandy clay |
| Tertiary | Clay, shale and sandstone |
| Upper Gondwana | Gondwana shale and clay |
| Archaean | Granite, gneiss and charnockite |
by interpretation of Indian Remote Sensing satellite’s Linear Imaging Self Scanning sensor III system (IRS LISS-III) imagery which is of 23.5 m spatial resolution. The geological map thus prepared was validated through field verification (Figure 2). Crystalline rocks of Archaean age comprising gneiss and charnockite forms the basement. Upper Gondwana series of shale and clay deposits lie over these crystalline rocks. Tertiary and Quaternary deposits lie over the Upper Gondwana formation (Rao et al. 2004). Quaternary deposits consisting of laterite are exposed as a small patch in the north west corner and alluvium of clayey sand is exposed in most parts of the area. Salt marsh occurs as patches in the eastern part of the area near the coast.

Hydrogeology

Tertiary formation comprising clay, shale and sandstone occurring below the alluvium has very low porosity and hydraulic conductivity. The alluvial deposits comprise sand, gravel and clay with a considerable amount of porosity and hydraulic conductivity. The alluvial deposits are characterized by the number of clay lenses, especially at the top, and the deposit is divided into two water bearing layers by clay of about 3–5 m thickness, which function as an aquitard (Figure 3). Hence, the upper part of the alluvium functions as an unconfined aquifer and the lower part functions as a semi-confined aquifer. The presence of two water bearing formations was confirmed by field measurements of groundwater head in the shallow dug wells (less than 15 m depth) and deep bore wells (greater than 20 m depth) located closer to each other. The groundwater head measured was different between the shallow and deep wells indicating the presence of two aquifers. The hydraulic conductivity of the upper aquifer ranges from 35 to 100 m/day and specific yield ranges from 0.10 to 0.15. Hydraulic conductivity of the lower aquifer varies from 45 to 250 m/day and storage coefficient varies in the range between 0.0014 and 0.0083 (UNDP 1987). Thus, the hydraulic conductivity of the lower aquifer is much higher compared to the upper aquifer. Owing to this the lower semi-confined aquifer functions as a major aquifer and it yields a large quantity of groundwater compared to the upper aquifer. Figure 3 shows a west to east geological cross section along line A–A’.

Model formulation and grid design

The study region was conceptualized from a detailed study of geology, lithologs and groundwater head fluctuations in the monitoring wells. The study area of 554 km² was discretized into finite element mesh consisting of 23,278 triangular finite element cells. To precisely evaluate the groundwater head near the coast, the eastern part was discretized into much smaller cells. Thus, the size of a finite element varies from 1,000 (in the east) to 24,000 m² (western side). The aquifer of 50 m thickness was divided into 25 layers.
with a layer thickness of 2 m. The top 7 layers represent the upper unconfined aquifer and layers from 10 to 25 represent the lower semi-confined aquifer (Figure 4). The aquitard is represented by layers 8 and 9.

**Boundary and initial conditions**

As the eastern side of the model area is bounded by the Bay of Bengal, it was considered as a constant head boundary. As the northern and southern boundaries are watershed boundaries, they were considered as no flow boundary. Up to a distance of about 2 km in the north east and south east boundary was considered as constant head boundary as it consists of canals and back water. The two rivers flowing in this region were considered as river head boundary and the time variant river stage was assigned. The rivers up to a distance of about 5 km from the sea were considered as constant head boundary as they have saline backwaters from the sea throughout the year. As the western boundary was fixed arbitrarily, it was considered as variable head boundary and time varying head was assigned based on the groundwater head observed in the nearby wells. Groundwater head during the month March 1988 was assigned as initial condition.

**Aquifer characteristics**

Aquifer properties such as hydraulic conductivity and specific yield of the upper and lower aquifers were assigned based on geology and from pumping test results conducted by UNDP (1987). The vertical hydraulic conductivity for semi-confining (aquitard) layer is 0.001 m/day (UNDP 1987).

**Groundwater recharge**

Rainfall is the principal source of groundwater recharge as compared to irrigation return flow, seepage from river and water storage ponds. The Groundwater Resource Estimation Committee (GEC 1997) recommended two approaches for estimating groundwater recharge in India, namely groundwater level fluctuation and specific yield method and rainfall infiltration method. In the present study, as the monthly recharge needed to be calculated for modelling, the method of rainfall infiltration was considered. In the absence of any other field measurements of rainfall recharge, the approach suggested by GEC (1997) was used to estimate recharge for carrying out modelling to predict the groundwater head. The rainfall recharge was thus estimated for different geological formations of the study area using the methods suggested by the GEC (1997). Estimation of groundwater recharge by this method may not be very precise but such a method only will be feasible to estimate time variant recharge over the entire area. There are two rain gauge stations at Vallur anicut and Ponneri; apart from them the rain gauge station at Chozhavaram, located just south of the study area, was also considered to calculate rainfall recharge. Based on the location of rain gauge stations, the model area was divided into different zones by Theissen polygon method. Further, each Theissen polygon was subdivided based on the geology and then the rainfall recharge was calculated. The spatial variation in percentage of groundwater recharge from rainfall is shown in Figure 5. Percentage of groundwater recharge from rainfall for various geological formations is given in Table 2. There is only minor variation in recharge, as the groundwater model area comprises alluvium. The Arani and Korttalaiyar rivers flow only during the monsoon seasons (October–December) and the average depth of the water in the river is about 1 m. Therefore, river stage of 1 m was assigned for river head boundaries in locations where the monthly rainfall was over 500 mm. Surface water bodies contain water only during monsoon periods, and since no water level measurements were available, recharge from the ponds was estimated by assuming pond water levels of 50 cm during the months in which rainfall exceeds 500 mm. As groundwater is pumped for irrigation, 39% of pumped water was considered as irrigation return flow, as estimated by Anuthaman (2009).
Groundwater pumping

Groundwater in the area is used for irrigation, domestic, industrial and municipal water supply. Groundwater pumping rate can be calculated by the consumption of electricity by the pumps and by crop water requirement. It is very difficult to calculate groundwater pumping from electricity consumption and pump type, because electricity is distributed free of cost by the Tamil Nadu government for irrigation. Hence, groundwater pumped for irrigation was estimated based on the crop water requirement during different seasons of the year by using satellite remote sensing data (Rajaveni et al. 2014). Landuse pattern was derived from Indian Remote Sensing satellite LISS-III imagery and is shown in Figure 6. About 61% of land has been utilized for agricultural purposes and the agricultural activity depends on groundwater except for during monsoon periods. Water requirement for different crop types were obtained from the report of Department of Agriculture, Tamil Nadu and it was used to calculate the rate of groundwater pumped for irrigation. Based on crop types and amount of water required for each crop, groundwater pumping was estimated to be 284 MCM/y. Groundwater requirements for domestic and industrial purposes was calculated from built-up area based on the population of the particular area with per capita demand. The calculated pumping for domestic and industrial purposes is about 1.94 MCM/y and 4.13 MCM/y. Groundwater pumping for aquaculture and saltpan activities are much less compared to irrigation, domestic and industrial pumping, and hence this was not considered. In addition, groundwater is being continuously pumped from well fields located in Minjur, Panjetty and Kanigaipar to supply water to Chennai city. The rate of groundwater pumping from these wells was obtained from Chennai Metro Water Supply and Sewerage Board (CMWSSB).

Model calibration

Model calibration is essential to assess how close the input parameters used are to the real field condition. Model calibration involves changing input parameters within the allowable range in order to attempt to match field conditions within some acceptable criteria. The model was calibrated under steady and transient state conditions. As in the period of March 1988, the groundwater head was between the extreme values measured in December and July, this period was chosen as initial head. Steady state calibration was carried out to get a better match between the
observed and simulated groundwater head by varying the aquifer parameters. Temporal variation in groundwater head from five monitoring wells in the upper and 10 monitoring wells from lower aquifers was collected from Public Works Department, Tamil Nadu and groundwater head measured in March 1988 was used for steady state calibration. Hydraulic conductivity and specific storage values were assigned based on the geological formation, subsurface lithological variations and pumping test (UNDP 1987) data. A number of trial runs were made to minimize the difference between observed and simulated groundwater head. At the end of trial runs the trend of observed and simulated head variation was more or less similar and the $R^2$ value for regression line was greater than 0.8 (Figure 7). Transient state calibration was carried out for a period of 15 years from March 1988 to December 2002 with 30-day time step. Transient state calibration was conducted to fine tune the values of input parameters. Time varying input parameters, such as river water level, groundwater recharge and pumping were given and the transient state calibration was carried out until the best possible match was obtained between observed and simulated groundwater heads. At the completion of several runs of the transient state calibration, the $R^2$ value for regression line was 0.899 and 0.864 between the observed and simulated heads in the upper and lower aquifers, respectively (Figure 7). The aquifer parameters used initially and those obtained after calibration are given in Table 3.

Simulation of groundwater head

The predictive simulation capability of the calibrated groundwater model was verified by validation. The validation of the model was carried out by comparing the simulated groundwater head with the observed heads for the period January 2003 to December 2012 with parameters arrived after calibration. Time series of observed and simulated groundwater head of upper (Well No. 1 and 5) and lower (Well No. 8, 12 and 19) aquifer wells are shown in Figures 8 and 9. There was a reasonable match between the observed and simulated groundwater head during the period considered for validation. Spatial variations in observed and simulated

![Figure 7](https://iwaponline.com/hr/article-pdf/47/1/42/368966/nh0470042.pdf)
groundwater head in upper and lower aquifers for some time periods are shown in Figures 10 and 11. This indicates that the model parameters used are able to reproduce the observed heads and thus the simulation capacity of the model was validated. The west–east cross section of the simulated groundwater head during some time periods is shown in Figure 12 which is used to understand the groundwater flow pattern in upper and lower aquifers. A similar trend of variation in groundwater head in the upper and lower aquifers indicates that contribution of vertical downward flow from the upper aquifer occurs, i.e., high groundwater pumping from the lower aquifer results in leakage of water from the

**Table 3** Initial and calibrated hydraulic conductivity and storage coefficient values

<table>
<thead>
<tr>
<th>Geology/Pumping test locations</th>
<th>Hydraulic conductivity, K (m/d)</th>
<th>Specific yield/Storage coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
<td>Calibrated</td>
</tr>
<tr>
<td>Upper aquifer (based on the geology)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beach sand</td>
<td>110</td>
<td>100</td>
</tr>
<tr>
<td>Silty sand</td>
<td>85</td>
<td>75</td>
</tr>
<tr>
<td>Clayey sand</td>
<td>50</td>
<td>65</td>
</tr>
<tr>
<td>Laterite</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Lower aquifer (based on pumping tests (UNDP 1987))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kattur</td>
<td>75</td>
<td>100</td>
</tr>
<tr>
<td>Interface</td>
<td>118</td>
<td>100</td>
</tr>
<tr>
<td>NE Minjur</td>
<td>228</td>
<td>250</td>
</tr>
<tr>
<td>Duranallur</td>
<td>69</td>
<td>50</td>
</tr>
<tr>
<td>Panjetti</td>
<td>118</td>
<td>85</td>
</tr>
</tbody>
</table>

**Figure 8** Temporal variation in observed and simulated groundwater head (m msl) for (a) Well no.1 and (b) Well no. 5 in the upper aquifer.
upper aquifer through the aquitard. The severe decline in groundwater head of around $-35$ m from mean sea level (msl) was noted in the drought years of 2004 and 2005 (Figure 9(a)). Groundwater pumping from the Minjur and Panjetty well fields by the water supply agency was stopped in the year 2005 due to this severe decline in groundwater head. As a result of the termination of pumping from these well fields in 2005, the groundwater head started to increase in 2006; however, the groundwater head is still $-15$ m msl. Since the groundwater head is below the sea level, this region has been affected by seawater intrusion over a long period. To overcome the problem of seawater intrusion, it is very important to identify the recharge and pumping strategies. Before implementing aquifer management strategies, it is also necessary to assess the sensitivity of parameters used in the model. The possible uncertainty in the outcome of the model can be understood by sensitivity analysis explained in the following section.

**Sensitivity analysis**

Uncertainty of model parameters is assessed by sensitivity analysis. Sensitivity analysis is the method of changing the model input parameters within the reasonable range and to evaluate the responses on model prediction. Sensitivity analysis is used to recognize the influence of input parameters on the simulated groundwater head and also to understand the sensitivity of one input parameter compared to other input parameters. Sensitivity of input parameters such as horizontal hydraulic conductivity, vertical hydraulic conductivity and specific storage was assessed by increase and decrease of 10%. As there is a possibility of about 10% difference in the values of aquifer parameters used (Table 3), sensitivity analysis was performed for this variation. Figure 13 shows the sensitivity of the model for changes in horizontal hydraulic conductivity values. Groundwater head increased by about 0.4 m to 1.0 m and
Figure 10 | Spatial variation in observed and simulated groundwater head in the upper aquifer.
Figure 11 | Spatial variation in observed and simulated groundwater head in the lower aquifer.
it decreased by about 0.4 m to 1.0 m while decreasing and increasing the horizontal hydraulic conductivity by 10%, respectively. Figure 14 shows the sensitivity of the model for changes in vertical hydraulic conductivity values. Groundwater head varied by about ±0.5 m while decreasing and increasing the vertical hydraulic conductivity by 10%. Figure 15 shows the sensitivity of the model for the changes in specific storage. There were very minor changes in groundwater head by about ±0.1 m, while increasing and decreasing of specific storage by 10%. Wide variation in groundwater head was observed while varying the horizontal hydraulic conductivity by ±10%. Thus, it is understood that horizontal hydraulic conductivity is the very sensitive parameter and it should be estimated more accurately. However, in this study the uncertainty in the values of hydraulic conductivity were minimized by using the values derived from the pumping tests.

**Aquifer response for changes in recharge and pumping**

It is observed that groundwater head in the lower aquifer has declined to the maximum during the years 2004 and 2005. The major reason for this is due to over-pumping of wells to meet the huge demand for Chennai city’s water supply during the years 2002, 2003 and 2004 when the rainfall was 28%, 34% and 16% below the normal annual rainfall, respectively. Based on the estimate given by Touche & Sivaprasakam (1992), about 35 MCM/y of groundwater was pumped for the city’s water supply during the years 1987–1990, which means that the groundwater pumping from this aquifer during the years 2003–2005 would have
been definitely greater than 35 MCM/y. On the other hand, the average groundwater pumped by local farmers for agricultural activity is 310 MCM/y (UNDTCD 1980). The above statement proves that this coastal aquifer is affected by over-exploitation. The projected rainfall by climate change models (INCCA 2010) indicates increased rainfall in the 2030s with respect to the 1970s is about 4.4%. Further, the maximum increase in rainfall is projected to occur in March, April and May in the 2030s, with rainfall set to increase by 14 mm on an average with respect to the same period in the 1970s (INCCA 2010). The climate prediction indicates a standard deviation of about 130 mm in the projected rainfall in the year 2030 (INCCA 2010), which is about 10% of the present annual rainfall of 1,200 mm. For the projected climate change in the northern parts of Tamil Nadu where the study area is located, the rainfall is likely to increase and the water yield to rise by 10–40% (INCCA 2010). Therefore, the groundwater model was used to study the impact of the projected changes in rainfall on the coastal aquifer. The expected increase in rainfall will result in a corresponding increase in groundwater recharge by about 10%. On the other hand, demand for water is increasing and there is a huge gap in demand and supply for Chennai city. Owing to this, groundwater pumping
from the western part of the study area is likely set to increase by about 10% by the year 2030. Accordingly, the model was used to predict the groundwater flow from the year 2013 to 2030 with the normal recharge and pumping conditions. A total of eight scenarios were considered:

- Scenario 1: 10% increase in rainfall recharge and normal pumping
- Scenario 2: 10% decrease in rainfall recharge and normal pumping
- Scenario 3: 10% increase in pumping

**Figure 16** | Predicted groundwater head by varying rainfall recharge by ±10% in a few wells.
- Scenario 4: 10% increase in rainfall recharge with 10% increase in pumping
- Scenario 5: 10% decrease in rainfall recharge and 10% increase in pumping
- Scenario 6: 10% decrease in pumping
- Scenario 7: 10% decrease in rainfall recharge and 10% decrease in pumping
- Scenario 8: 10% increase in rainfall recharge and 10% decrease in pumping.

Figure 16 shows the predicted groundwater head by the model under Scenarios 1 and 2 in a few wells located in the upper and lower aquifer at different distances from the sea, i.e., the effect of variation by ±10% in rainfall with the current level of pumping. When the rainfall recharge was increased by 10% the groundwater head will increase by about 2 m in upper and lower aquifers (Table 4), whereas when the rainfall recharge was decreased by 10% the groundwater head will decrease by about 1 m in the upper aquifer and 1.5 m in the lower aquifer (Figure 16). There was a maximum of 1 and 0.5 m difference in groundwater head of the upper aquifer and lower aquifers (Table 4). The effect of a 10% increase in groundwater pumping from the lower aquifer with ±10% variation in rainfall recharge on groundwater head is shown in Figure 17. This figure shows the predicted groundwater head by the model under Scenarios 3, 4 and 5 in a few wells located in the upper and lower aquifer at different distances from the sea. If the pumping is increased by 10% the groundwater head decreases by about 1 m in the upper aquifer and 4 m (Table 4) in the lower aquifer by the year 2030. On the other hand, if the rainfall recharge is increased by 10% (Scenario 4) the groundwater head increases by 1 m in the upper aquifer and declines by 2.5 m in the lower aquifer. Model prediction for a 10% decrease in rainfall recharge (Scenario 5) indicates the decline of groundwater head from 1 to 1.5 m in the upper aquifer and from 3.5 to 5 m in the lower aquifer (Table 4). A maximum of 1 and 2.5 m difference in groundwater head was observed in upper and lower aquifers in Scenarios 3, 4 and 5. Figure 18 shows the predicted groundwater head for Scenarios 6, 7 and 8, i.e., the effect of 10% decrease in groundwater pumping coupled with variation in rainfall by ±10%. When the pumping is decreased by 10% and considering a normal rainfall recharge (Scenario 6), the predicted groundwater head increases from about 1–3.5 m in the upper and lower aquifers. Predicted groundwater head for a 10% decrease in pumping and rainfall recharge (Scenario 7), decreases the head by 1 m in the upper aquifer and 2 m in the lower aquifer. Predicted groundwater head for a 10% decrease in pumping and rainfall recharge (Scenario 7), decreases the head by 1 m in the upper aquifer and 2 m in the lower aquifer.

### Table 4 | Effect of increase/decrease in rainfall recharge and pumping on groundwater head by the end of year 2030

<table>
<thead>
<tr>
<th>Scenario number</th>
<th>Description</th>
<th>Upper aquifer</th>
<th>Lower aquifer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Eastern side (Well no. 2)</td>
<td>Western side (Well no. 5)</td>
</tr>
<tr>
<td>1</td>
<td>10% increase in rainfall recharge</td>
<td>Increase by 2 m</td>
<td>Increase by 1.7 m</td>
</tr>
<tr>
<td>2</td>
<td>10% decrease in rainfall recharge</td>
<td>Decrease by 1 m</td>
<td>Decrease by 0.8 m</td>
</tr>
<tr>
<td>3</td>
<td>10% increase in pumping</td>
<td>Decrease by 1 m</td>
<td>Decrease by 0.8 m</td>
</tr>
<tr>
<td>4</td>
<td>10% increase in rainfall recharge with 10% increase in pumping</td>
<td>Increase by 1 m</td>
<td>Increase by 0.8 m</td>
</tr>
<tr>
<td>5</td>
<td>10% decrease in rainfall recharge and 10% increase in pumping</td>
<td>Decrease by 1.5 m</td>
<td>Increase by 1 m</td>
</tr>
<tr>
<td>6</td>
<td>10% decrease in pumping</td>
<td>Increase by 1 m</td>
<td>Increase by 0.8 m</td>
</tr>
<tr>
<td>7</td>
<td>10% decrease in rainfall recharge and 10% decrease in pumping</td>
<td>Increase by 1 m</td>
<td>Increase by 0.8 m</td>
</tr>
<tr>
<td>8</td>
<td>10% increase in rainfall recharge and 10% decrease in pumping</td>
<td>Increase by 5 m</td>
<td>Increase by 1.8 m</td>
</tr>
</tbody>
</table>
Predicted groundwater head for a 10% decrease in pumping and 10% increase in rainfall recharge (Scenario 8), increases the head from 1.8 m to 3 m in the upper aquifer and from 4.5 m to 6 m in the lower aquifer, respectively. A maximum of 2.5 m and 4 m difference in groundwater head was observed in the upper and lower aquifers in Scenarios 6, 7 and 8. From the model prediction for all scenarios considered, it is understood that the 10% increase of rainfall recharge and 10% decrease of groundwater pumping causes 3 m and 6 m increase in groundwater head in upper and lower aquifers (Table 4), respectively, by the end of year 2030.
Thus, as expected, intervention with pumping and rainfall recharge will help to restore this aquifer and increase the groundwater head (Figure 18). The groundwater recharge in this area can be increased by managed aquifer recharge structures such as construction of check dams across the rivers and construction of percolation ponds as well as by rejuvenation of existing surface water bodies. Parimalarenganayaki & Elango (2015) estimated that about 1.3 MCM of water is recharged from October 2010 to May 2011 through the construction of a single check dam in the Arani river. Percolation pond is another method to increase local groundwater recharge. A preliminary assessment by
the interpretation of satellite image indicated the possibility of construction of several percolation ponds. Groundwater pumping for agriculture purposes can be reduced by creating the awareness in farmers for cultivating less water intensive or drought tolerant crops during low rainfall periods. Groundwater pumping by the CMWSSB from Minjur and Panjetty well fields has already been stopped (due to salinization). Thus, the increase of groundwater recharge and decrease of well field pumping is an achievable task to restore this heavily exploited coastal aquifer. The present study shows that this coastal aquifer will replenish in another 20 years if groundwater recharge is increased by 10% and pumping is decreased by 10%.

CONCLUSION

Finite element groundwater flow modelling was carried out for the north of Chennai coastal aquifer for assessment of response of the aquifer system for changes in groundwater recharge due to the projected climate change and groundwater pumping. The model predicts the groundwater head with a reasonable level of accuracy. Further, the model was validated by comparing the monthly simulated and observed groundwater head for a long period, that is from January 2003 to December 2012. The model was then used to assess the response of changes in pumping and the projected changes in climate on rainfall until the year 2030. Groundwater head was predicted until the year 2030 under eight different scenarios to assess the response of groundwater level to the changes due to pumping and rainfall variation due to climate change. It is inferred that a 10% increase in rainfall recharge due to climate change and 10% decrease in groundwater pumping will lead to a 5 m and 6 m increase in groundwater head in upper and lower aquifers, respectively, by the end of year 2030. Thus, as expected, intervention in pumping and rainfall recharge will help to mitigate the problem of seawater intrusion. Groundwater recharge in this area can be increased by managed aquifer recharge structures such as construction of check dams and percolation ponds as well as by rejuvenation of existing surface water bodies. The projected increase in rainfall due to climate change and the recharge structures will help to increase the groundwater recharge by 10%. Groundwater pumping for agriculture can be reduced by providing proper awareness to farmers and suggestions to cultivate drought tolerant crops during low rainfall periods. Groundwater pumping from Minjur and Panjetty well fields has already been stopped due to salinization of groundwater. Thus, the increase of groundwater recharge and decrease of well field pumping is an achievable task to restore this heavily exploited coastal aquifer. Prediction of groundwater head by modelling indicated that this coastal aquifer will replenish in another 20 years if groundwater recharge is increased by 10% and pumping is decreased by 10%. Thus, groundwater modelling was used to assess possible measures to overcome the problem of seawater intrusion in the next 20 years in this aquifer.

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