

Evaluation of Impact of Climate Change on Seawater Intrusion in a Coastal Aquifer by Finite Element Modelling

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Abstract: Climate change and increase of population is expected to affect coastal groundwater systems in many parts of the world. Changes in the rainfall pattern due to climate change may also lead to uncertainties in the supply and management of the groundwater resources. The objective of this study is to evaluate the impact of climate change on seawater intruded coastal aquifer located north of Chennai, India by density dependent groundwater modelling and to identify suitable measures of mitigation. This aquifer system is affected by seawater intrusion since the year 1969 due to over extraction of groundwater for agriculture and drinking water supply to Chennai city. Since the climate change projections for this area is available until the year 2030, the density-dependent model was used to predict the changes in hydrological stresses on the groundwater head until this year. The impact of sea level rise on seawater intrusion was noticed up to about 5 km from the coastline. The 10% increase in rainfall recharge with an additional check dams and 1 m increase in crest level of all the existing check dams is expected to increase the groundwater head by about 3 m in the upper and 5.5 m in the lower aquifers. This will also decrease the chloride concentration by about 1000 mg/l in the upper and 700 mg/l in the lower aquifers respectively. Thus, the construction of Managed Aquifer Recharge structures along with the 10% increase of rainfall pattern due to climate change will decrease the chloride concentration and restore in this seawater intruded aquifer in future.

Keywords: Climate change, Water resource, Groundwater head, Seawater intrusion, Arani-Korttalaiyar.

Introduction

Global warming increases the temperature of land surface, oceans and seas. The warming will also decrease the atmospheric pressure, which will result in increase in the sea level. The sea level will rise by 10 mm with a one millibar decrease in atmospheric pressure (Sherif and Singh, 1999). A series of depressions in atmospheric pressure can cause a considerable rise in water levels in shallow ocean basins (Theon, 1993). Change in climatic variables can significantly alter groundwater recharge rates in major aquifer systems and thus affect

the availability of fresh groundwater. Groundwater resources are related to climate change through the direct interaction with surface water resources such as lakes and rivers and indirectly related through the recharge process (Jyrkama and Sykes, 2006). The direct effect of climate change on seawater intrusion depends upon the change in the volume and distribution of groundwater recharge (Kumar, 2016). Venetsanou et al. (2016) estimated the impacts of rainfall change due to climate change on groundwater balance of a coastal aquifer. Climate change will affect coastal groundwater resources due to sea level rise and increase seawater

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intrusion into fresh water aquifer (Yang et al., 2015). The sea level rise and variations in the groundwater recharge rates are the important factors controlling the seawater intrusion and degradation of the chemical quality of the groundwater in the coastal aquifers (Barazzuoli et al. 2008). Mazi et al. (2013) studied the tipping points for seawater intrusion due to the rising of sea level. About 14% of people in India are living in or near 7517 km long coast line. Groundwater is used as a major source of water by the people living in coastal regions. Over pumping of groundwater in the coastal regions lead to seawater intrusion.

The expected climate change in this region may result in increase of rainfall and water yield by about 10% to 40% by the year 2030 (INCCA, 2010). According to SAARC Meteorological Research Centre (SMRC, 2002) and Intergovernmental Panel on Climate Change (IPCC, 2007) report, the sea level rise between seasons appears to be higher in the Bay of Bengal than other regions in south Asia. A 50 cm rise in the Bay of Bengal sea level will cause an additional intrusion of 0.4 km (Sherif and Singh, 1999). Chennai is the fourth largest metropolitan city in India located on the coast of Bay of Bengal where seawater intrusion is a major problem due to over pumping of groundwater. The seawater has intruded up to a distance of about 14 km in the aquifers located north of Chennai (Indu et al., 2013). Rao et al. (2004) simulated groundwater flow in the north Chennai coastal aquifer by using a sharp interface model developed by the United States Geological Survey. Charalambous and Garratt (2009) studied the recharge and the abstraction relationship through finite element model in the Arani-Korttalaiyar

groundwater basin. These studies have not considered the density dependent groundwater flow to simulate the climate change effects. It is also essential to assess the various options to overcome the problem of seawater intrusion under the changing climate scenarios. Hence, the present study was carried out with the objective of evaluating the impact of climate change on seawater intruded coastal aquifer located north of Chennai, India by density dependent groundwater modelling and to identify suitable measures of mitigation.

Description of the Study Area

This study was carried out in the Arani-Korttalaiyar river basin located at a distance of about 45 km north of Chennai metropolitan city (Figure 1). Chennai is the 4th largest metropolitan city located on the Coromandel Coast of the Bay of Bengal and it has the 3rd largest expatriate population in India. Seawater intrusion has been reported in this area since 1969 (UNDP, 1987). This region experiences a very dry (summer) period during April to June with a maximum temperature ranging from 28°C to 44°C and a colder (winter) period from December to January, when the temperature ranges from 23°C to 30°C. Relative humidity varies from 65% to 85% in the morning and varies from 40% to 70% in the afternoon (CGWB, 2007). Arani and Korttalaiyar rivers flowing in this basin are non-perennial rivers and they flow only for about a few days during northeast monsoon (October to December). Three well fields are located in the palaeo channels of Palar river in this area (Figure 1). Pumping of groundwater from the tube wells meet about 10% of the Chennai city's requirements.

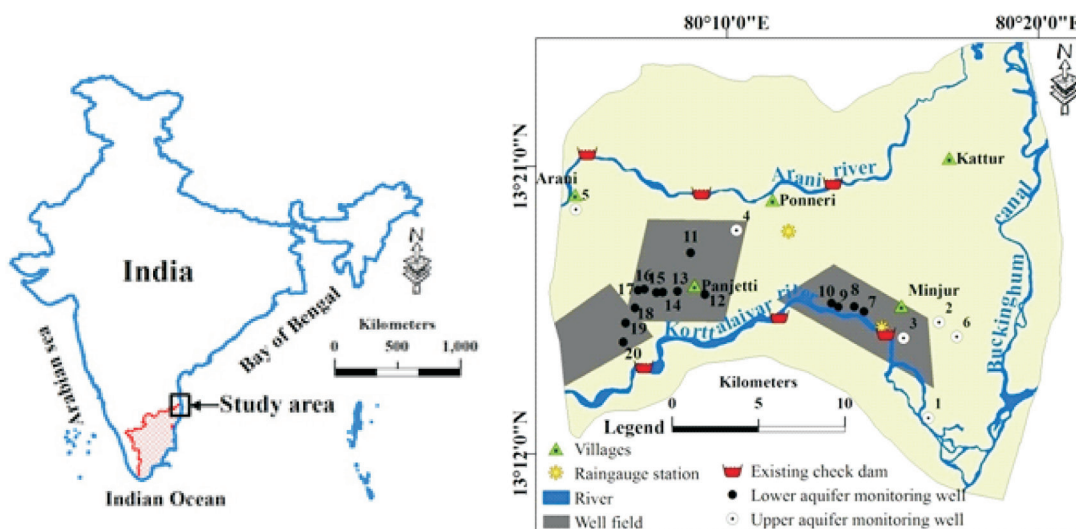


Figure 1: Study area showing the location of monitoring wells.

Methodology

Initially, a well inventory survey was carried out during January 2011 to locate the monitoring wells. Thereafter the groundwater head was measured in these wells once in two months from January 2011 to December 2013 by using a water level indicator (Solinst 101) and groundwater samples collected in the field were analyzed for the concentration of chloride in the laboratory by using an Ion Chromatograph (Metrohm). In order to convert the groundwater head measured below ground level with respect to the sea level, the elevation of the ground surface were measured using Differential Global Positioning System (DGPS) (Leica GS09 GNSS). Groundwater model of the area was created in three dimensions using Finite Element subsurface FLOW (FEFLOW 6.2 Version) software. 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).

Results and Discussion

Geology

Geologically this area comprises rocks from Archaean to Quaternary age. Crystalline rocks of Archaean age comprising gneiss and charnockite forms the basement. The upper Gondwana formation of shale and clay deposits lie over these crystalline rocks which is overlain by Tertiary and Quaternary formations. Tertiary formation consists of shale, clay, sandstone and marine sediments. Quaternary formation comprises massive pile of lacustrine and fluvial deposits (Rao et al., 2004b). Alluvial deposits consist of sand, silt, sandy clay, gravel and pebbles which mostly occur along the Arani and Korttalaiyar river courses. Geological map of the area obtained from Geological Survey of India in 1:50,000 scale was updated by interpreting the Indian Remote Sensing Satellite (IRS)1D Linear Imaging Self-scanning Sensor-III (LISS-III) imagery (2006) which is of 23.5 m spatial resolution. Geological map thus prepared was validated through field visits and is shown in Figure 2.

Hydrogeology

The characterization of the aquifer system in this area was made by interpreting the borehole logs collected from Chennai Metropolitan Water Supply and Sewerage Board (CMWSSB) and private drilling companies. An

exploratory well drilled north of Panjetti to a depth of about 750 m by the Central Ground Water Board, penetrated through 40 m alluvium followed by Tertiary and Gondwana formations (UNDP, 1987). Thus, the thickness of the alluvium is generally 50 m and all the lithologs collected from the CMWSSB are up to the Tertiary clay. The geological cross section prepared by interpreting the lithologs located along the aquifer zones is shown in Figure 3. The aquifer comprises fine to coarse sand, sand with gravels and pebbles, sandy clay and several small patches of clay occurring as lenses. Tertiary formation of clay and shale function as impermeable layers and as the bottom of this aquifer system.

In order to confirm the nature of the aquifer system in this region an intensive field investigation was carried out to measure the groundwater head in several wells. The dug wells in this area are generally less than 20 m deep and tube wells are up to 120 m deep. About 10 pairs of dug and tube wells located next to each other were chosen to measure groundwater head. The groundwater head was measured in these pairs of dug wells and deep tube wells located very close to each other during July 2012. The groundwater head measured in these pairs of shallow and deep wells were different confirming the presence of two aquifers. Hence, the lower aquifer functions as a semi-confined aquifer whereas the upper aquifer is an unconfined aquifer. The groundwater head in the unconfined aquifer ranges from 2 to 6 m bgl (below ground level) and in the semi-confined aquifer it ranges from 14 to 20 m bgl.

Groundwater Recharge and Abstraction

Rainfall infiltration is the main source for groundwater recharge. Rainfall collected from three rain gauge stations was compared with the groundwater head in the upper aquifer monitoring wells (Figure 4). Comparison between the rainfall and the groundwater head indicates that 15% of the rainfall recharges to the aquifer is equivalent to the specific yield of the upper aquifer. Even though, this is an approximate method of estimation of groundwater recharge, the percentage of rainfall recharge determination is comparable with the estimate given by GEC (1997) for this area. Based on the geology and the location of rain gauge stations, the area was divided into Thiessen polygons to define monthly groundwater recharge. Based on the previous studies and GEC (1997) norms, the groundwater recharge was assigned from 12% to 17%. 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 (Rajaveni et al., 2015). A return flow from agricultural field also contributes to groundwater recharge. Charalambous and Garratt (2009) and Anuthaman (2009) estimated that 39% of irrigation water returns to this aquifer. Hence, 39% of water pumped was considered as irrigation return flow.

Groundwater in the region is abstracted for various purposes such as local agricultural and domestic uses as well as for water supply to Chennai. Different direct and indirect methods have been used by several researchers (Rajaveni et al., 2015) to estimate the rate of groundwater pumping. Groundwater abstraction rate can be estimated directly from the hourly consumption of electricity, horsepower of pump and indirectly by using crop water requirement for irrigation. As the electricity is provided free of cost to the farmers in the study area,

the groundwater pumping cannot be estimated from the consumption of electricity directly. Further, it is a difficult task to estimate the exact operating hours of the pumps in the study area. Hence, indirect method of crop water requirement method was adopted to calculate the groundwater pumping (Rajaveni et al., 2015). In this method, the groundwater pumping is calculated by multiplying the water requirements of each type of crop with its corresponding area. IRS 1D LISS-III imagery was used to prepare land use map of this area. The landuse pattern was classified into paddy, sugarcane, vegetable, plantation, current fallow, permanent fallow, wetlands, water bodies, educational institutions, industrial, residential, waste land and forest. Based on crop types and amount of water required for each crop, groundwater pumping was estimated to be 284 MCM/y (Rajaveni et al., 2015). The groundwater pumping for the domestic use was calculated based on per capita demand as 1.94 MCM/year (Rajaveni et al.,

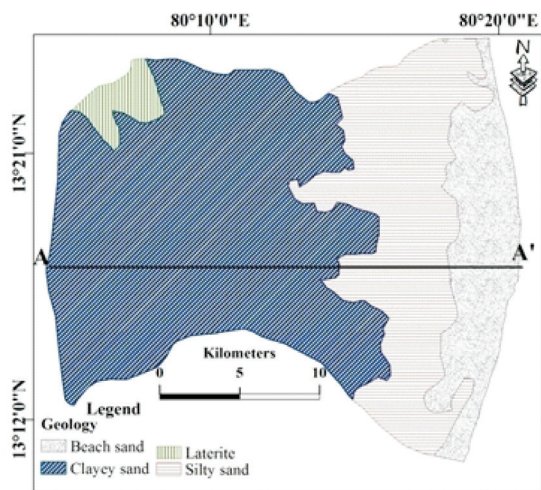


Figure 2: Geology of the study area.

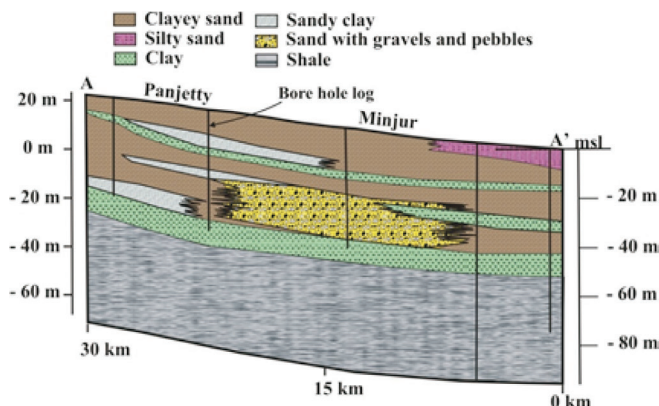


Figure 3: Subsurface geological cross section along A-A' of Figure 2.

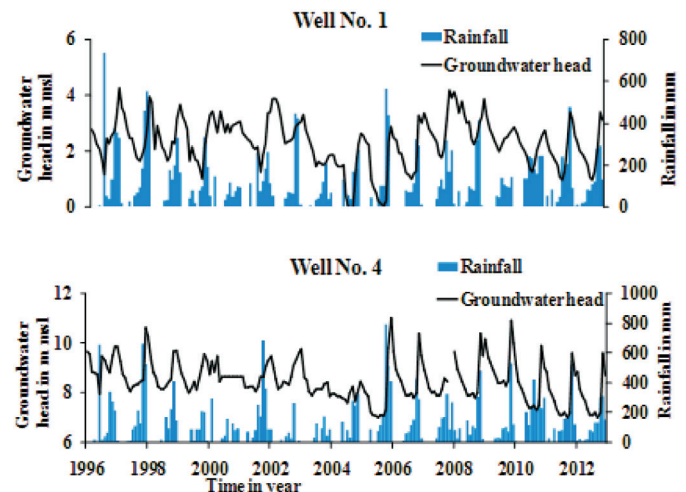


Figure 4: Monthly variation in rainfall and groundwater head in a few wells of upper aquifer.

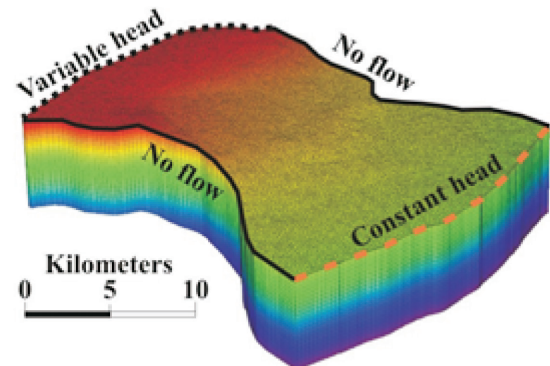


Figure 5: Three-dimensional discretization of the area and boundary conditions.

2015). The actual rates of groundwater pumping of wells of CMWSSB were obtained and it is about 120 MLD (from 15 years average).

Model Formulation

Groundwater model of the area was created in three dimensions using Finite Element subsurface FLOW (FEFLOW 6.2 Version) software. The study area was conceptualized based on the geology, subsurface geology and groundwater head fluctuations. The model area was discretized into 23,278 small triangular elements. The aquifer thickness of 50 m was divided into 25 layers with 2 m layer thickness. The top seven layers represent the upper unconfined aquifer. The aquitard is represented by layers 8 and 9. The layers from 10 to 25 represent the lower semi-confined aquifer (Figure 5).

Boundary and Initial Conditions

Numerical models require an appropriate set of boundary conditions to represent the real aquifer system relationship with the surrounding area. The different boundary conditions assigned for the model of the study area are shown in Figure 5. As the northern and southern boundaries are watershed boundaries, they were considered as no flow boundary. As the eastern side of the model area is bounded by the Bay of Bengal, it was considered as a constant head boundary. Time dependent groundwater head in this boundary was assigned from the groundwater head observed in the wells on either side of the boundary. The two rivers flowing in this region were considered as river head boundary. The chloride concentration of 500 mg/l in river water was estimated from the laboratory analysis. Based on the study of groundwater head at different months it was observed that the groundwater head in the month of January 1996 was more stable and not affected by pumping. Hence, the groundwater head measured during January 1996 was considered as an initial head.

Aquifer Parameters

Aquifer parameters such as hydraulic conductivity, porosity and specific yield were assigned to each element based on pumping tests carried out by UNDP (1987). Specific yield of the aquifers was assigned based on the values given by Todd and Mays (2005) and Fetter (2001) for different geological formations. The hydraulic conductivity of the upper aquifer varies from 35 m/day to 100 m/day and for aquitard it varies from 0.001 m/day to 0.01 m/day. Hydraulic conductivity of the lower aquifer varies from 100 m/day to 250 m/day.

Density-dependent Parameters for Seawater Intrusion
Parameters such as molecular diffusion, longitudinal dispersivity, transverse dispersivity and density ratio that are necessary to consider the density difference in groundwater was assigned to account for freshwater-seawater interactions. Longitudinal dispersivity, transverse dispersivity and coefficient of molecular diffusion were considered as 66.6 m, 6.6 m and 1×10^{-6} m²/s respectively as reported by Sherif and Singh (1999). Density ratio was calculated based on the density of freshwater and seawater as 1000 kg/m³ and 1025 kg/m³ respectively to represent the density variation.

Model Calibration and Validation

Groundwater Head

Model calibration is a process in which some of the key input parameters are varied to achieve simulated groundwater heads similar to that of measured head. Model calibration consists of changing values of model input parameters in an attempt to match field conditions within some acceptable criteria. The calibration process typically involves calibrating to steady-state and transient conditions. The steady state calibration was carried out by trial and error method to reduce the difference between observed and simulated groundwater head. After successfully calibrating the steady state condition, model was used to calibrate under transient state condition for the period from January 1996 to December 2003 by using automatic time steps with initial time step of 0.001 day. Aquifer parameters arrived from the steady state calibration and the other input parameters were used in transient state calibration. Time varying input parameters such as groundwater recharge and pumping were assigned. Comparison between the observed and simulated groundwater heads after the transient state calibration is shown in Figure 6.

Further, the density-dependent groundwater model was validated with the input parameters derived

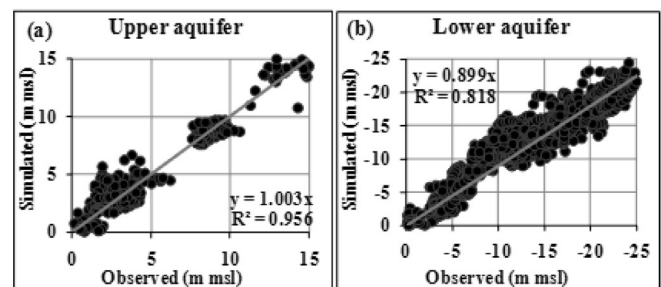


Figure 6: Comparison between the observed and simulated groundwater heads after the transient state calibration.

from calibration for the period from January 2004 to December 2012. There was a reasonable match between the observed and simulated groundwater head. This indicates that the model with the assigned input parameters is able to reproduce the observed heads and thus the prediction capacity of the model was tested. Temporal variation in the observed and simulated groundwater head in the upper and lower aquifers are shown in Figure 7.

Density-dependent Modelling of Seawater Intrusion

After calibrating and validating the groundwater model, simulation of chloride concentration was made. In order to match the observed and simulated values of chloride, several runs were made by slightly varying the longitudinal and transverse dispersivity values by trial and error method. Chloride ion was chosen as it is a conservative ion and hence it is not affected by geochemical reactions. Several simulations were made and finally a reasonable match between the observed and the simulated values were obtained for longitudinal and transverse dispersivity values of 70 m and 7 m respectively. The diffusion coefficient was not changed during these runs. The measured concentration of chloride from the upper and lower aquifers was compared to the simulated chloride (Figure 8). It shows a reasonable match between the measured and simulated chloride concentration.

Climate Change Effects on Groundwater Head

The seawater intrusion can be mitigated by improving groundwater recharge and reduction in pumping. The groundwater recharge can be improved by several methods such as spreading ponds, modification of

pumping pattern, artificial recharge, extraction barrier, injection barrier and subsurface barrier (Todd and Mays, 2005). In order to increase the groundwater head and decrease the chloride concentration in this aquifer affected by seawater intrusion various Managed Aquifer Recharge (MAR) methods can be considered. The possible methods of MAR in this area are construction of check dams and increase of crest level of the existing check dams.

The study of the elevation of the river bund indicates that it is possible to increase the crest level of the existing check dams by 1 m. This will enhance the storage in the check dam which in turn increases the groundwater recharge. Climate change and sea level rise represent critical parameters affecting the rate and degree of seawater intrusion (Abd-Elhamid et al., 2016). IPCC (2007) report concluded that the sea level along the Bay of Bengal coast has increased by 0.9 mm between 1937 and 1991. In the year 2030, it is expected to rise about 10 cm in Bay of Bengal (IPCC, 2007). Further, 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 1200 mm. The rainfall is likely to increase the water yield by 10% to 40% (INCCA, 2010). So, the model was run under different scenarios of implementation of MAR structures, sea level rise and climate change to identify measures to mitigate the seawater intrusion from the year 2016 to 2030. The scenarios considered are:

- Scenario 1: Sea level rise by 0.5 m
- Scenario 2: With additional check dams and 1 m increase in crest level of all the existing check dams

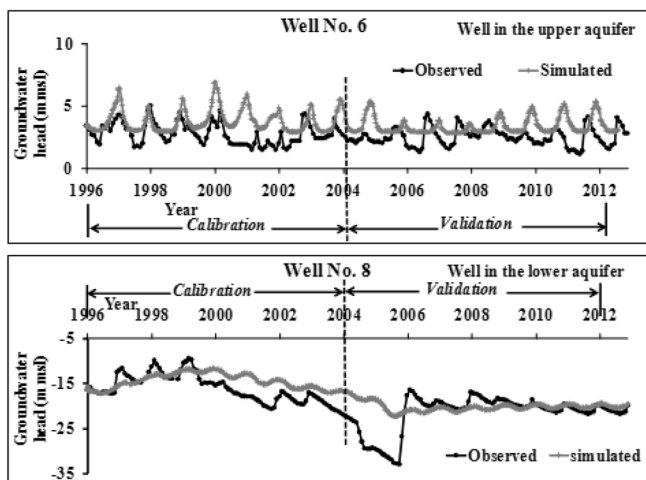


Figure 7: Temporal variation in the observed and simulated groundwater head.

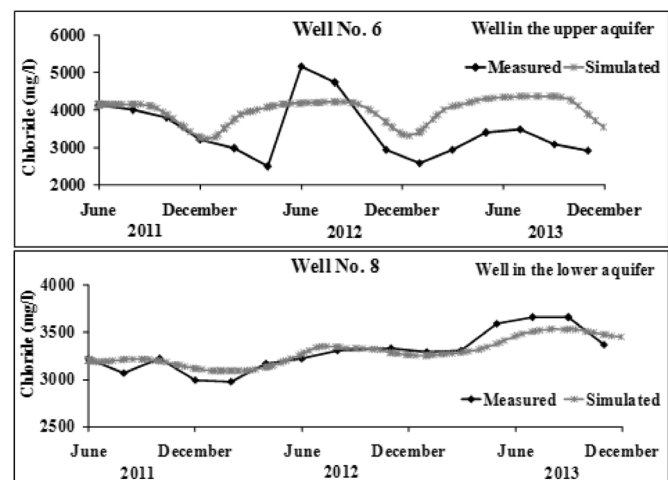


Figure 8: Temporal variations in the measured and simulated chloride concentration.

- Scenario 3: 10% increase in rainfall recharge due to climate change with scenario 2

Figure 9 shows the predicted groundwater head by the model for all the three scenarios in wells located in the upper and lower aquifer at different locations. The model predicts that in the upper aquifer, the groundwater head increases by about 0.4 m in a well closer to the sea by sea level rise (scenario 1). However, groundwater level in regions far away from the sea has not been affected by the 0.5 m sea level rise. Only aquifers with very low hydraulic gradients are more vulnerable to sea-level rise (Ferguson and Gleeson, 2012). In the lower aquifer, a marginal increase was observed in the groundwater head under scenario 1. The model predicts that in the upper aquifer, the groundwater head increases by about 2.8 m upto a distance of 1 km from the check dams by scenario 2. In the lower aquifer, the groundwater head increases by about 2.5 m by scenario 2. For scenario 3, the groundwater head increases by about 3 m in the upper aquifer and 5.5 m in the lower aquifer.

Figure 10 shows the predicted chloride concentration by the model for all the three scenarios in wells located in the upper and lower aquifer at different locations. The model predicts that the chloride concentration increases by about 300 mg/l in the upper and lower aquifers for 0.5 m rise of sea level (scenario 1). However, this effect is due to the assumption of rise in sea level from the year 2016. The model predicts that the chloride concentration decreases by about 550 mg/l and 300 mg/l in the upper and lower aquifers respectively by the increase in crest level of the existing check dams by 1 m and additional check dams (scenario 2). Predicted

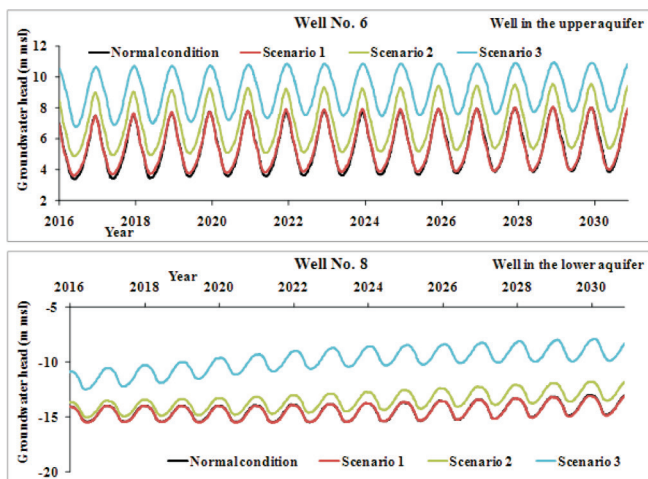


Figure 9: Predicted groundwater head for various scenarios.

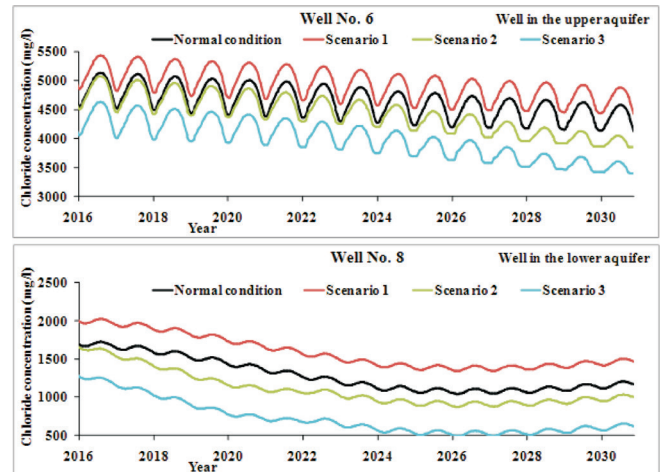


Figure 10: Predicted chloride concentration for various scenarios.

result shows that the chloride concentration decreases by about 1000 mg/l and 700 mg/l in the upper and lower aquifers respectively in the case of scenario 3. Thus, the increase of groundwater recharge due to climate change, increase in crest level of the existing check dams by 1 m and additional check dams is feasible to restore this heavily exploited coastal aquifer.

Conclusion

Density-dependent groundwater flow modelling was carried out for the part of north Chennai coastal aquifer for the evaluation of impact of climate change on groundwater storage and seawater intrusion. The developed model was validated and it is able to simulate the groundwater head with reasonable level of accuracy. The model was used to predict the effect of projected climate change and sea level rise on groundwater head. The groundwater head is expected to increase by about 3 m and 5.5 m in the upper and lower aquifers respectively by the end of year 2030 due to increase in rainfall and the implementation of possible MAR measures. The chloride concentration decrease by about 1000 mg/l and 700 mg/l in the upper and lower aquifers. The projected increase in rainfall due to climate change and the recharge structures will help to increase groundwater head and decrease considerable amount of chloride concentration and to restore this seawater intruded aquifer system in near future.

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