Journal of Environmental Informatics 15(1) 33-41 (2010)

Journal of Environmental Informatics

www.iseis.org/jei

Application of Solute Transport Modeling to Study Tsunami Induced Aquifer Salinity in India

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Received 12 January 2009; revised 22 July 2009; accepted 6 August 2009; published online 12 March 2010

ABSTRACT. Natural processes such as flooding, earthquakes, tsunami, sea water intrusion and rock-water interaction processes will all result in deterioration of groundwater quality. One such natural catastrophic event, in the form of a massive tsunami occurred on December 26, 2004, triggered by a 9.2 magnitude earthquake off the west coast of Sumatra, killed more than 2,50,000 people and displaced thousands in countries around the Indian Ocean. Extensive damage is not only to the life and property but also for deterioration of groundwater quality in coastal regions. Study of processes of salinization of groundwater by tsunami and the time that it might take for the natural recharge processes to flush this salinity is of great importance. The study area includes a portion of Kalpakkam region situated in the Kancheepuram District of Tamil Nadu state in southern India. A groundwater model was developed to simulate the groundwater flow and solute concentration in the study area. Finite element code FEFLOW 5.2 was used for this purpose. The model was used to simulate groundwater flow and solute transport for a period of two years from January 2005 to January 2007. The results indicate that tsunami-induced salinity in this aquifer system would be flushed out with normal annual rainfall by the year 2008-09. The post audit results also confirms that the model have been calibrated and simulated with high accuracy. The present work has demonstrated the application of groundwater modeling to understand the process of salinisation of groundwater resources by tsunami. It has also helped to determine the time that it would take for remediation of the aquifer system by rainfall recharge.

Keywords: Tsunami, inundation, salinisation, solute transport, sandy aquifer, southern India

1. Introduction

Natural catastrophic event, in the form of a massive tsunami occurred on December 26, 2004, triggered by a 9.2 magnitude earthquake off the west coast of Sumatra, killed more than 250,000 people and displaced thousands in countries around the Indian Ocean. Tsunami waves entered inland up to 0.2 ~ 1 km, caused extensive damage to life and property to all the coastal districts along the east coast of Tamil Nadu, India. There were major impacts of the tsunami on infrastructure and human life; it also resulted in change of groundwater quality in the coastal regions. Study of processes of salinisation of groundwater by tsunami and the time that it might take for the natural recharge processes to flush this salinity is of great importance.

Number of studies have been carried around the world on the impact of tsunami by Szczucinski et al. (2005), Chaudhary et al. (2006), Srinivasalu et al. (2008), Illangasekare et al. (2006) and for groundwater management and solute transport by Prickett et al. (1981), Linda and Bredehoeft (1987), Storm and Mallory (1995), Gomboso et al. (1996), Koskinen et al. (1996), Holzbecher (1998), Storm (1998), Gnanasundar and Elango (2000), Zhou et al. (2000), Faidi et al. (2002), Senthil Kumar and Elango (2002) and Eiswirth et al. (2004). However, none of these studies attempted to study the salinisation processes and the time that it might take to flush tsunami-induced salinisation with the help of solute transport model. Hence, the present work was carried out to understand the salinisation processes and the time that it might take to flush tsunami-induced salinisation with the help of solute transport model in the Kalpakkam region, Tamil Nadu, India

A network of 20 wells was established and these wells are spread throughout the study area and were monitored monthly for a period of 26 months from January 2005 to February 2007. Of these six wells were located in the tsunami-inundated zone (well number 1, 2, 8, 9, 11 and 12) of the study area. The samples were analyzed for concentrations of major, minor and trace elements. The inundated zone extends to about 200 to 500 m from the present shoreline (Figure1). These wells, which generally penetrate up to a depth of 7 to 10 m below the ground surface, are fitted only with hand pumps, and the abstraction from these wells is very less. During field investigations, it was found from the well-owners living in the inundated zone that the water in this region was potable before the tsunami. Further, it is found that there are no previous reports on the presence

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ISSN: 1726-2135 print/1684-8799 online
 doi:10.3808/jei.201000164

of saline water in the wells located in this region before the tsunami event. After the tsunami, however, the groundwater quality deteriorated in these wells by the increase in EC (Electrical Conductivity) upto 12,800 μS/cm.

There are two possible reasons for the salinisation of this aquifer by tsunami: 1) direct contamination of wells by entry of sea water through hand pumps and 2) infiltration of sea water into the aquifer through the unsaturated zone. Thus in this region sea water would have directly entered into the aquifer through the inundated wells as well as percolated through the unconsolidated sediments in this region during tsunami resulting in salinisation of groundwater.

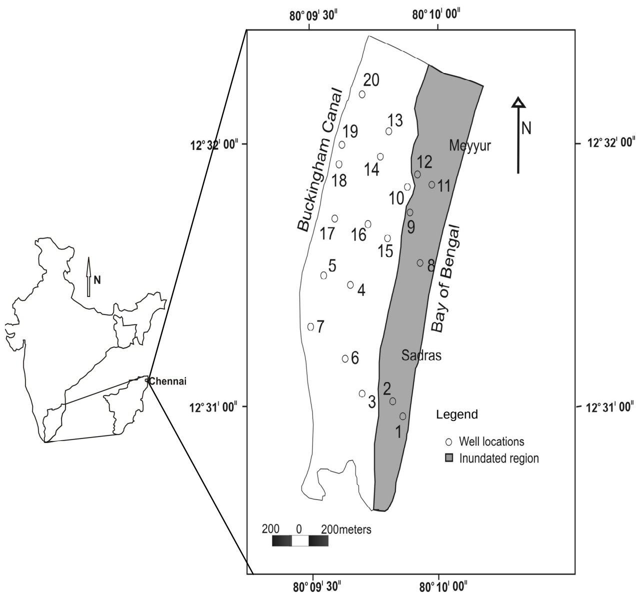

Figure 1. Location of study area with location of sampling wells.

A part of the saline water would be retained in the unsaturated zone during the process of infiltration through the unsaturated zone. The water retained in the unsaturated zone may deposit the salts during evapotranspiration, which are flushed in during subsequent rainfall recharge. Thus, this mechanism will result in the long-term threat to groundwater quality.

1.1. Study Area

The study area forms a portion of the Kalpakkam region situated in the Kancheepuram district of Tamil Nadu state in southern India. The study area is located at 75 km south of Chennai City (formerly Madras), and covers an area of 2 km^2 extending about 2 km along the north-south and about 1 km along the east-west directions. The villages namely Sadras, Meyyur and Kalpakkam township are located near this area. Groundwater from this coastal aquifer was used for drinking as well as for agricultural purposes. Agricultural activity is practiced in some parts of the villages of Sadras and Meyyur.

Climate of this area is characterized by an oppressive hot summer, dampness in atmosphere nearly throughout the year and good seasonal rainfall. The maximum temperature in this area is about 44 °C during the months of April, May, June and July. The minimum temperature is about 22 °C during the months of December and January. Mean annual precipitation at Kalpakkam exceeds 1300 mm (CGWB, 2001), most of which falls during the northeast monsoon (October to December). Heavy rains in the study area are often associated with depresssions and storms, which generally occur in the Bay of Bengal during the northeast monsoon.

1.2. Hydrogeology

Physiographically, the study area is elevated in the center and slopes towards east and west. The highest elevation was measured in the northeastern part of study area, about 7.5 m above the mean sea level (msl). Geologically, this study area has two distinct formations: crystalline charnockite rocks of Archean age and Quaternary/Recent sediments. Crystalline charnockite are overlain by Quaternary/Recent sediments (CGWB, 2001). The Quaternary sediments consists of sand and clayey sand. The Quaternary/Recent sediments, weathered and fractured crystalline charnockite function as an unconfined aquifer system. The groundwater head follows the topography, that is, it flows towards east and west from the central part of the area. The water table surface changes over time in response to climatic conditions, land use, and groundwater withdrawals.

Groundwater requirement of this area is mostly met by wells penetrating upto upper Quaternary/Recent sediments. In some regions, hand pumps, shallow wells fitted with small motor pumps are used by the households. Similar number of bore wells with submersible pumps are used for irrigation. Only limited quantity of groundwater is pumped for irrigation. Apart from this the township located in Sadras region is also provided with piped water supply from the nearby Palar river basin.

1.3. Modelling Technique

Groundwater flow of the study area was simulated using a finite element model. The computer software program FEFLOW 5.2 developed by the Institute for Water Resources Planning and Systems Research, Germany, was used in the present study. FEFLOW is a version of the modular finite element simulation system for modelling 3D and 2D flow, mass and heat transport processes in groundwater and unsaturated conditions. In this study, the model was used for both saturated and unsaturated conditions.

1.4. Groundwater Flow Equation

Groundwater flow equations are formulated by combining the equation of motion in the form of Darcy's Law with the mass balance equation (also known as mass conservation equations or continuity equations) for specific aquifer systems. The groundwater flow through a porous medium can be expressed two dimensionally by the following partial differential equation (Rushton and Redshaw, 1979):

$$\frac{\partial}{\partial x}(K_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial h}{\partial y}) = S_s \frac{\partial h}{\partial t} + W \quad (1)$$

where K_x and K_y are the hydraulic conductivities along x and y directions, h is the potentiometric head in meters, W is the volumetric flux per unit volume (m/day), S_s is the specific storage, and t is the time.

1.4.1 Mass Transport Equation

The mass transport equation can be derived from the principle of conservation of mass by considering all fluxes into and out of a representative elementary volume (Bear, 1972). The mass transport equation can be expressed as:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}(D_{ij} \frac{\partial C}{\partial x_{ij}}) - \frac{\partial}{\partial x_i}(v_i C) + \frac{qs}{\theta} C_s + \sum_{k=1}^{N} R_k \quad (2)$$

where C is the concentration of contaminants dissolved in groundwater, in ML^3, t is the time, x_i is the hydrodynamic dispersion coefficient, L and D_{ij} are the coefficients of hydrodynamic dispersion.

The first term on the right hand side of the equation represents the change in concentration due to hydrodynamic dispersion, while the second gives the effect of advective transport. The third term represents source/sink, while the last term represents the chemical reaction.

2. Modeling Formulation

Model conceptualization is a set of assumptions and hypothesis that facilitate the quantification process. The model was conceptualized with the help of geological and geoelectrical data and water level fluctuations in the wells of the study area.

2.1. Aquifer

Groundwater occurs in this area in the Quaternary unconsolidated sediment formations. All the wells located in this area penetrate only these sediments (sand and clayey sand). 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.

2.2. 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 in its east, Buckingham Canal in its west, and backwaters in 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.

2.3. Grid Design

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 grids. Thus, the study area was discretised into 720 nodes with 639 elements encomposing a total area of approximately 2 km^2 (Figure 2).

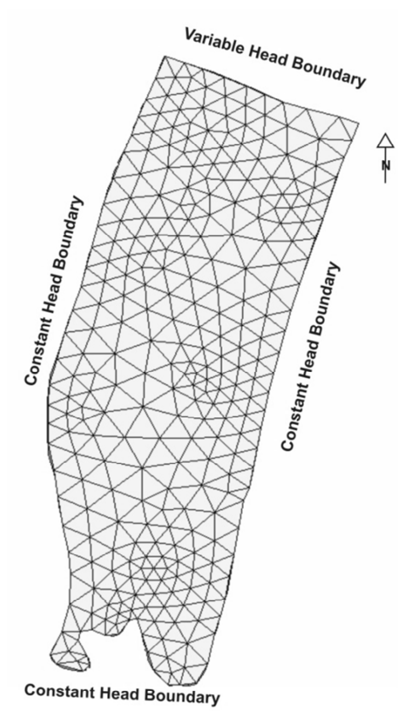

Figure 2. Discretisation of the area and the boundary conditions.

2.4. Input Parameters

(1) Aquifer Characteristics

The aquifer properties, such as specific yield, horizontal hydraulic conductivity and vertical hydraulic conductivity, were assigned to each cell based on the data obtained from the Central Ground Water Board (CGWB, 2001) and are listed in Table 1. 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.

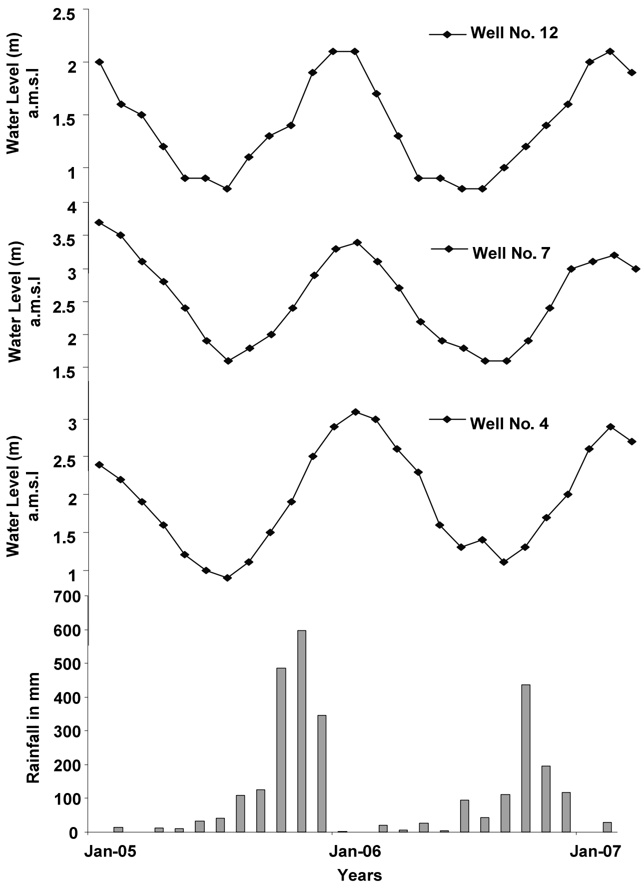

Figure 3. Seasonal variations in groundwater head and Rainfall.

(2) 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 agricultural purposes and is based on the electricity consumption and area of irrigation (CGWB, 2001). This abstraction is distributed over the study area which is based on land use patterns. Similar analogy was used for simulating Chennai coastal aquifer (Gnanasundar and Elango, 2000) which is hydrogeologically similar to the present study area.

(3) Groundwater Recharge

The monthly recharge rate had assigned to the model area with the help of rainfall and groundwater level relationship graph which is shown in Figure 3. 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 higher than 100 mm. When the monthly rainfall was greater than 100 mm, 45% of it was assumed as recharge. For the areas near the Buckingham Canal, recharge was considered to vary between 25 and 35% due to the presence of clayey sand in these regions.

Table 1. Aquifer Parameters Used in the Model

Aquifer parameter	Range
Porosity	0.17-0.25
Specific yield (S_y)	0.1-0.27
Horizontal hydraulic conductivity (K_h), m/day	27-45
Vertical hydraulic conductivity (K_h), m/day	12-18
Longitudinal dispersivity (a_L), m	5-12.5
Transverse dispersivity (a_T), m	0.5-1.2

(4) 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 1.5 to 3.4 m above msl. Potentiometric surface of the unconfined aquifer during this month is given in Figure 4.

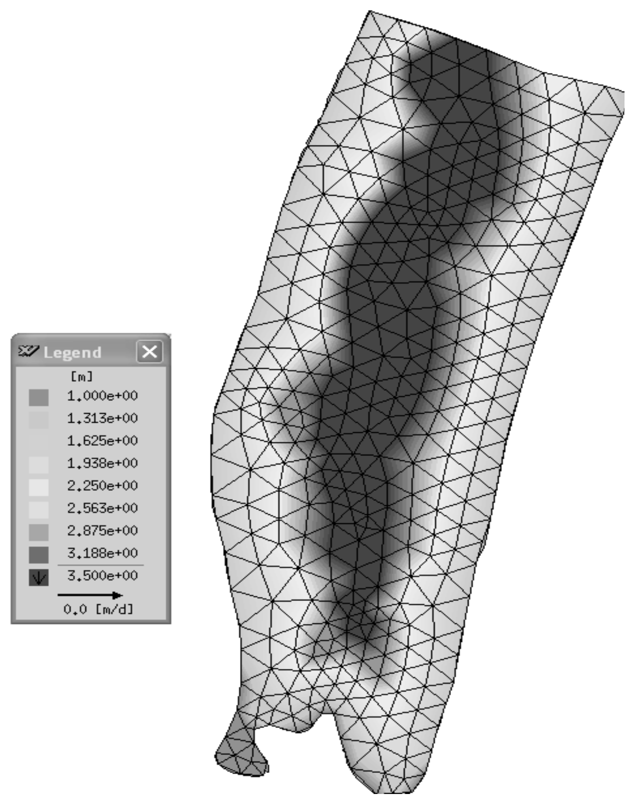

Figure 4. Initial groundwater head.

(5) Initial Concentration

The initial chloride concentration was used as input to the model which ranges 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.

2.5. 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. Steady state calibration was carried out to minimize the difference between the computed and the field water level conditions, with the water level data of December 2004. The density values for the fresh water and seawater for this model was considered as 1 and 1.025 respectively. The density of sea water of Bay of Bengal was reported as 1.022 (Reddy et al., 2009). Off all the input parameters, the hydraulic conductivity and specific yield values were the poorly-known, as only one pumping test had been carried out in this area. Based on lithological variations, it was decided to vary hydraulic conductivity and specific yield values up to 10% of the pumping test results in order to get a good match of the computed and observed heads.

The hydraulic conductivity and specific yield values arrived from the steady state calibration and the other initial input parameters were then used as the initial condition in the transient model calibration. The 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.

Table 2. Initial and Calibrated Hydraulic Parameters

Sl. No.	Aquifer material	Hydraulic conductivity (m/day)		Specific yield	
		Initial	Calibrated	Initial	Calibrated
1	Sand	45	55	0.27	0.34
2	Clayey sand	25	30	0.10	0.18

Calibration of transient model was achieved by number of trials to get a good match between computed and observed heads over space and time 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 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 hydraulic conductivity and specific yield after calibration are presented in Table 2.

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. 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.

3. Simulation Results

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

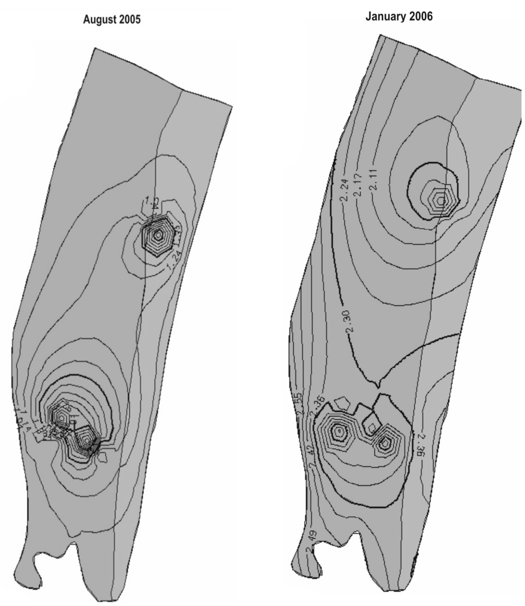

Figure 5. Simulated groundwater head for August 2005 and January 2006.

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 5. The computed groundwater heads of wells 4, 7 and 12 of the study area (Figure 6) mimic the observed values. In general, the simulated results indicate that this aquifer system is stable under the present pumping rate.

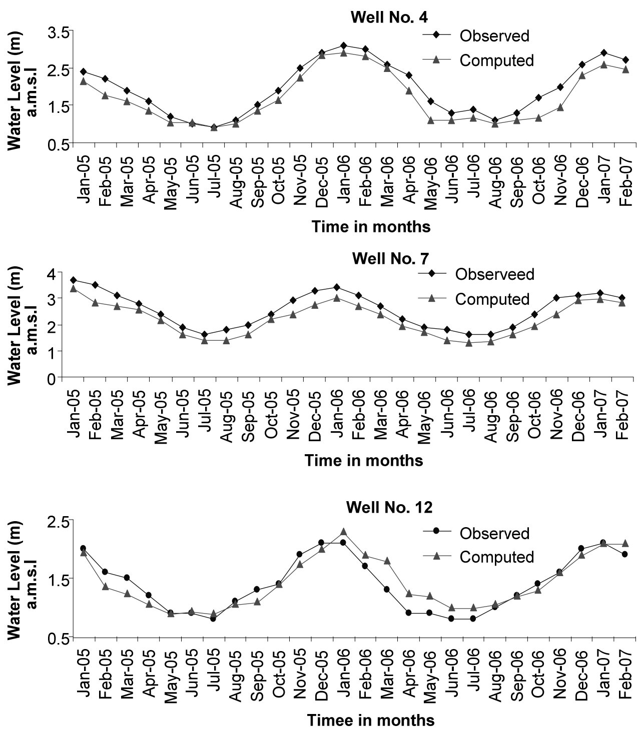

Figure 6. Comparison between simulated and observed groundwater heads.

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 transport was carried out. Even though concentration of all major ions was monitored it was decided to consider the transport of chloride only for modeling. As the chloride is the most dominant ion in the sea water and it is also a conservative ion, transport of 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 144^{th} 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.

Simulation of the concentration of chloride for the months of January 2005 to January 2007 was carried out. The chloride

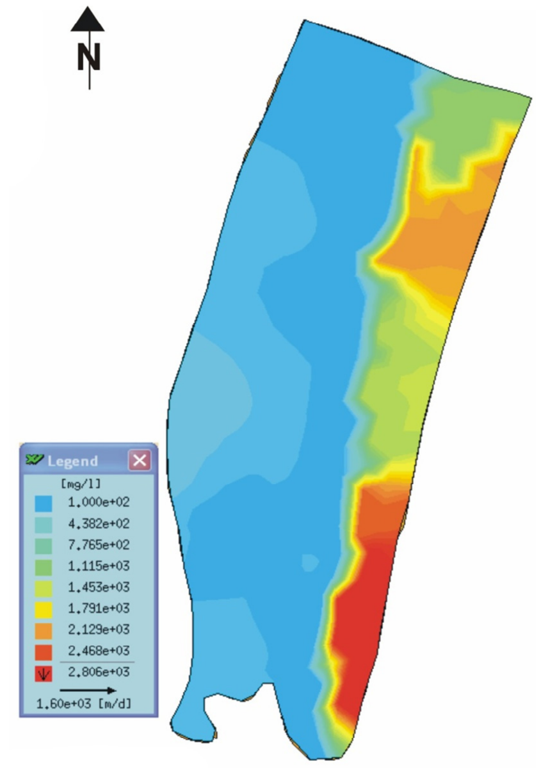

Figure 7. Simulated chloride ion concentration of groundwater in January 2005.

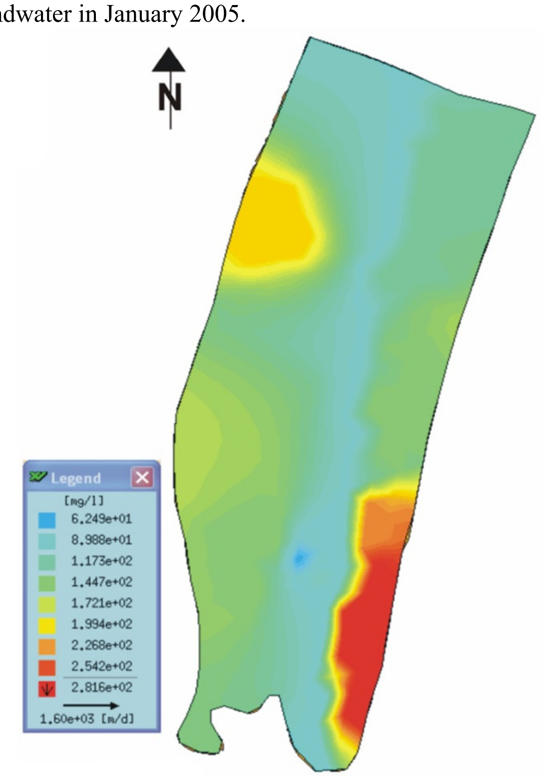

Figure 8. Simulated chloride ion concentration of groundwater in January 2007.

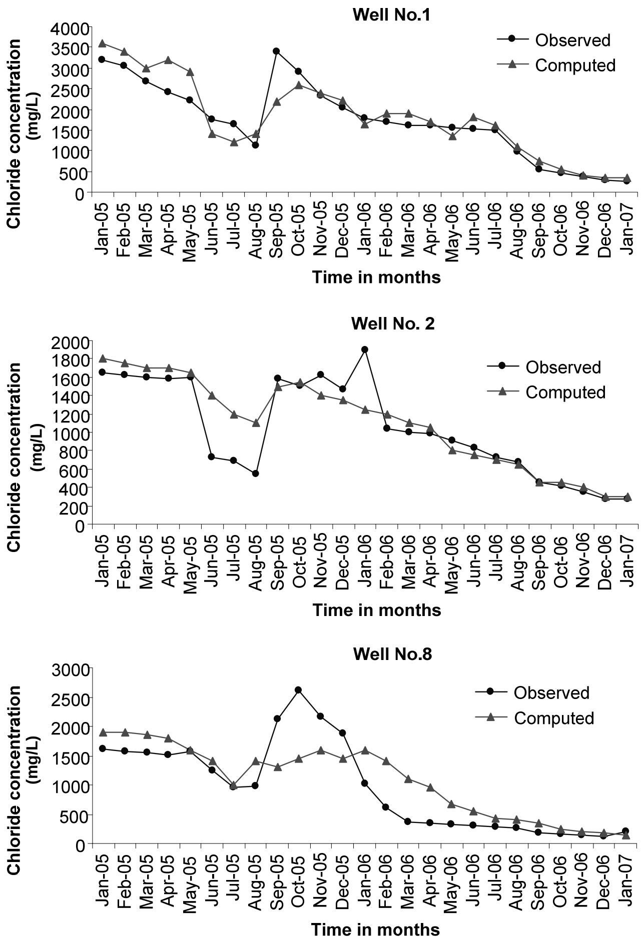

Figure 9. Computed and observed chloride concentration in well no 1, 2 and 8.

concentrations of January 2005 and January 2007 are shown in Figures 7 and 8, respectively. The computed and observed solute concentration of wells 1, 2, 8, 9, 11 and 12 are shown in Figures 9 and 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. This was due to the lateral flow of fresh water from the west. After the rain during the months of August and September 2005, the concentration of chloride ions increased in the inundated zone wells. This was due to the recharge of fresh water through the unsaturated zone, which resulted in washing of the salts deposited in the unsaturated zone due to the evaporation of sea water that entered during the tsunami. The salts in sediments brought by the tsunami might have also got flushed in by the recharging water. But at end of the 26 stress period, the chloride concentration was more along the south-eastern boundary of the study area.

3.1. Forecasting

The model developed for the Kalpakkam 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.

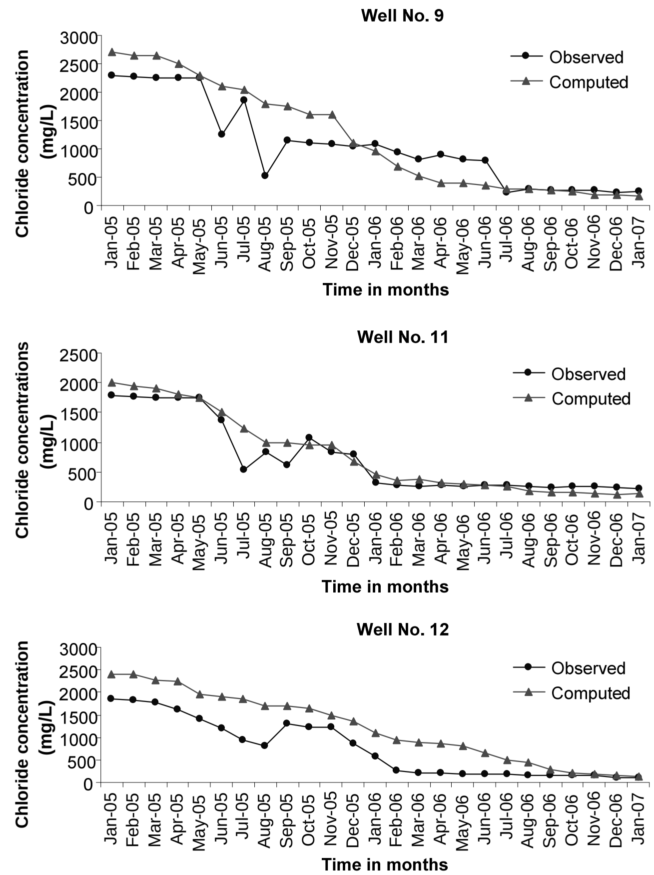

Figure 10. Computed and observed chloride concentration in well no 9, 11 and 12.

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 11. 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 12. 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 modeling carried out using this finite element model helped to understand the process of salinisation, and remediation of the aquifer by natural recharge. Post auditing was conducted to cross check the accuracy of the concentration of groundwater forecasted by the model in the tsunami affected region of the study area. This was done by the collection and analysis of groundwater samples after com-

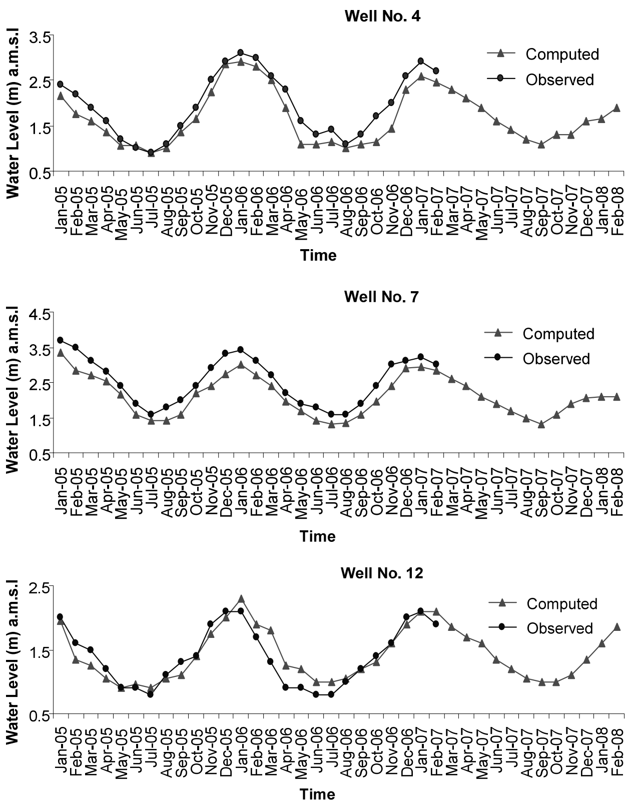

Figure 11. Predicted groundwater head until February 2008.

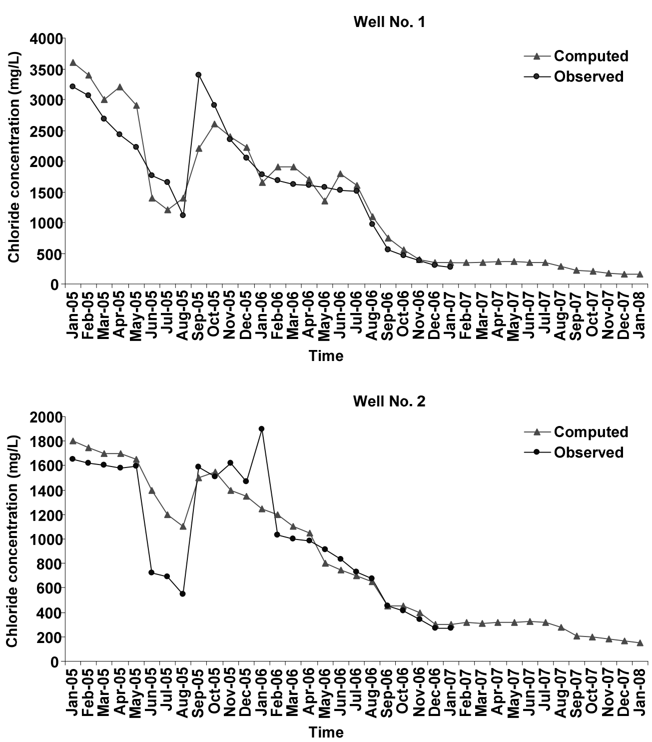

Figure 12. Predicted chloride ion concentration in January 2008.

pletion of the modeling work in the month of March 2008. The chloride concentration of groundwater from the well no. 1 was 276 mg/L and for well 2 it was 99 mg/L. The model predicted results of well 1 and 2 on January 2008 were 227 and 170 mg/L respectively. Thus, the predicted model results are reasonably matching with the post audit results which confirms that the model have been calibrated and simulated with reasonable accuracy.

3.2. Conclusions

Numerical modeling of the groundwater flow and transport was carried out, which simulated the effect of tsunami inundation. The simulated results match reasonably with the observed trends. This finite element model forecasts that the chloride concentration of the groundwater of this area will decrease and reach the pre-tsunami level by the end of the year 2008. The post audit result confirms that the model have been calibrated and simulated with high accuracy. The study carried out by finite element model, therefore, helped to understand the processes of salinisation and remediation of the aquifer by natural recharge. The present work has demonstrated the application of solute transport modeling to understand the process of salinization of groundwater resources by tsunami. It has also helped to determine the time that it would take for remediation of the aquifer system by rainfall recharge.

Acknowledgments. We wish to thank the financial support received under the UGC-CPEES and UGC-SAP schemes that helped to carry out this work.

References

Bear, J. (1972). *Dynamics of fluids in porous media Elsevier*, New York.

CGWB (2001). *Artificial recharge methods of groundwater in IGC-AR site*, Kalpakkam.

Chaudhary, D.R., Gosh, A., and Patolia, J.S. (2006). Characterization of soils in the tsunami-affected coastal areas of Tamil Nadu for agronomic rehabilitation, *Current Sci.*, 91(1), 99-104.

Eiswirth, M.L., and Wolf, H.H. (2004). Balancing the contaminant input into urban water resources, *Environ. Geol.*, 46, 246-256, doi:10.1007/s00254-004-0981-8.

Faidi, H.A., Garcia, L.A., and Albertson, M.M. (2002). Development of a model for simulation of solute transport in a stream-aquifer system, *Environ. Model. Assess.*, 7, 191-206, doi:10.1023/A:1016380806404.

Freeze, R.A., and Cherry, J.A. (1979). *Groundwater*, Prentice Hall Inc., New Jersey.

Ganasundar, D., and Elango, L. (2000). Groundwater modelling of a coastal aquifer near Chennai city, India, *Jour. Indian Water. Resour. Soc.*, 20 (4), 162-172.

Gomboso, J., Ghassemi, F., and Jakeman, A.J. (1996). Modeling groundwater flow in the North Stirling land conservation district Western Australia, *Ecol. modeling*, 80, 169-175, doi:10.1016 /0304-3800(95)00047-X.

Holzbecher, E. (1998). *Modeling Density-driven Flow in Porous Media,* Springer.

Illangasekare, T., Tyler, S. W., Clement, T. P., Villholth, K. G., Perera, A. P. G. R. L., Obeysekera, J., Gunatilaka, A., Panabokke, C. R., Hyndman, D. W., Cunningham, K. J., Kaluarachchi, J. J., Yeh, W.

W.G., Genuchten, M. T. V., and Jensen, K. (2006). Impacts of the 2004 tsunami on groundwater resources in Sri Lanka, *Water Resour. Res.,* 42, 1-9, doi:10.1029/2006WR004876.

Koskinen, L., Laitinen, M., Loefman, J., Meling, K., and Measzaaros, F. (1996). FEFLOW: a Finite element code for simulating groundwater flow, heat transfer and solute transport, *Development and Application of Computer Technique to Environmental Studies*, Computation Mechanics Publications.

Linda, B.D., and Bredehoeft, J.D. (1987). Origins of seawater intrusion in a coastal aquifer-a case study of the pajaro valley, California, *J. hydrology*, 92, 363-388, doi:10.1016/0022-1694 (87) 90 024-2.

Prickett, H.L., Naymik, T.G., and Lonnquist, C.G. (1981). A "random walk" solute transport model for selected groundwater quality evaluations, *Illinois State. Water Survey Bulletin.*, 65, 103.

Reddy, N., Aung, T., and Singh, A. (2009). Effect of the 2004 'Boxing Day' Tsunami on water properties and currents in the Bay of Bengal, *Am. J. Environ. Sci.*, 5(3), 247-255.

Rushton, K.R., and Redshaw, S.C. (1979). Seepage and groundwater flow, *John Wiley*, 1-330.

Senthil Kumar, M. and Elango, L. (2002). Rainfall and groundwater level relationship in a part of the Lower Palar River Basin, Tamil Nadu, India, *Sustainable Development and Management of Groundwater Resources in Semiarid Regions with Special Reference to Hard Rocks*, Oxford-IBH.

Srinivasalu, S., Thangadurai, N., Jonathan, M.P., Armstrong, J.S., Ayyamperumal, T., and Ram-Mohan, V. (2008). Evaluation of trace-metal enrichments from the 26 December 2004 tsunami sediments along the Southeast coast of India, *Environ. Geol.*, 53(8), 1711-1721, doi:10.1007/s00254-007-0777-8.

Storm, E.W., and Mallory, M.J. (1995), Hydrogeology and simulation of groundwater flow in the Eutaw-Mcshan aquifer and in the Tuscaloosa aquifer system in northeastern Mississippi, *U.S Geological Survey Water-Resources Investigations Report*, 94-42 23, pp. 83.

Strom, E.W. (1998), Hydrogeology and simulation of groundwater flow in the Cretaceous-Paleozoic aquifer system northern Mississippi, *U.S Geological Survey Water-Resources Investigations Report 98-4171*, pp. 81.

Szczucinski, W., Niedzielski, P., Rachlewicz, G., Sobczynski, T., Zioła, A., Kowalski, A., Lorenc, S., and Siepak, J. (2005). Contamination of tsunami sediments in a coastal zone inundated by the 26 December 2004 tsunami in Thailand, *Environ. Geol.,* 49, 321-331, doi:10.1007/s00254-005-0094-z.

Zhou, X., Chen, M., Ju, X., Ning, X., and Wang, J. (2000). Numerical simulation of sea water intrusion near Beihai, China, *Environ. Geol.,* 40, 1-2, doi:10.1007/s002540000113.