Simulation of Seawater Intrusion in Ernakulam Coast

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Abstract

The development and management of fresh groundwater resources in coastal aquifers are seriously constrained by the presence of seawater intrusion. Underutilisation of the available groundwater resource means that valuable fresh water discharges naturally to the sea and is wasted; overdevelopment, on the other hand, mines the resource and will cause a gradual degradation of water quality due to the encroachment of seawater. Over the years, many models have been developed to represent and study the problem of seawater intrusion. They range from relatively simple analytical solutions to complex numerical models. Ernakulam is one of the important ports in west coast of India. Due to increase in population, fast urbanisation and land reforms, the district is facing a number of environment problems such as flooding, groundwater pollution due to discharge of industrial effluents, seawater intrusion etc. There exists an urgent need to study systematically the causes and remedial measures for seawater intrusion. This paper presents the simulation of seawater intrusion in a section of Ernakulam coast through Saturated-Unsaturated TRAnsport (SUTRA) model and examines the impact of increased pumping scenarios on extent of seawater intrusion.

Introduction

Coastal zones contain some of the most densely populated areas in the world as they generally present the best conditions for productivity. However, these regions face many hydrological problems like flooding due to cyclones and wave surge, and drinking fresh water scarcity due to problem of salt water intrusion. The development and management of coastal groundwater aquifers is a very delicate issue. Intrusion of seawater has become one of the major constraints affecting ground water management. As seawater intrusion progresses, existing pumping wells, especially close to the coast, become saline and have to be abandoned, thus, reducing the value of the aquifer as a source of freshwater. As an aid to effective management, many models have been developed over the years to represent and study this problem. They range from relatively simple analytical solutions to complex state-of-art numerical models using large computing capacity.

Currently, several solute transport models, suitable for the simulation of seawater intrusion and upconing of saline water beneath pumping sites, are commercially available. These include SUTRA (Voss, 1984), FEFLOW (Diersch, 1998), HST3D (Kipp, 1987) and SALTFLOW (Molson and Frind, 1994). These models provide solutions of two simultaneous, non-linear, partial differential equations that describe the "conservation of mass of fluid" and "conservation of mass of salt" in porous media. SUTRA (Saturated-Unsaturated TRAnsport) employs a two-dimensional finite-element approximation of the governing equations in space and an implicit finite-difference approximation in time and is suitable for simulation of a vertical section of an aquifer that is subject to seawater intrusion. FEFLOW is a finite-element package for simulating 3D and 2D fluid density-coupled flow, contaminant mass (salinity) and heat transport in the subsurface. It can evaluate the impact of seawater intrusion due to groundwater pumping and/or mining activities along coastal regions. HST3D (Heat and Solute Transport in 3 Dimensions) employs three-dimensional finite-difference approximations of the governing equations. This model is capable of simulating an aquifer with irregular geometry. SALTFLOW is also three-dimensional but utilise a finite-element approximation of the governing equations for an aquifer that is subject to the intrusion of seawater.

Saturated-Unsaturated TRAnsport Model (SUTRA)

SUTRA is a finite-element simulation model for saturated-unsaturated, fluid-density-dependent groundwater flow with energy transport or chemically-reactive single-species solute transport. SUTRA may be employed for areal and cross-sectional modelling of saturated groundwater flow systems and for cross-sectional modelling of unsaturated zone flow. Solute transport simulation using SUTRA may be employed to model natural or man-induced chemical species transport including processes of solute sorption, production and decay and may be applied to analyse groundwater contaminant transport problems and aquifer restoration designs. In addition, solute transport simulation with SUTRA may be used for modelling of variable density leachate movement and for cross-sectional modelling of salt water intrusion in aquifers in near-well or regional scales with either dispersed or relatively sharp transition zones between fresh water and salt water. SUTRA energy transport simulation may be employed to model thermal regimes in aquifers, subsurface heat conduction, aquifer thermal energy storage systems, geothermal reservoirs, thermal pollution of aquifers and natural hydrogeologic convection systems. The following three versions of SUTRA have been released so far : Version V12842D (original version released in 1984), Version V06902D (first revision in 1990), and Version V09972D (second revision in 1997).

SUTRA is written in Fortran 77 including optional Fortran 90 statements allowing dynamic array allocation. Generally, the program is easily installed on most computer systems. The code has been used on a wide variety of computers, ranging from UNIX-based computers to DOS-based 386 computers with as little as 640K of RAM.

Governing Equations

The simulation of seawater intrusion requires the solution of partial differential equations that describe "conservation of mass of fluid" and "conservation of mass of solute". These are summarised below (Voss, 1984).

Conservation of mass of fluid

The fluid mass balance in a saturated porous medium can be expressed as:

$$\partial(\varepsilon\rho)/\partial t = -\nabla.(\varepsilon\rho V)+Q_p \quad \ldots(1)$$

where ε (x,y,z,t) is porosity; ρ (x,y,z,t) is fluid density; Q_p (x,y,z,t) is fluid mass source; V (x, y, z, t) is fluid velocity; x, y and z are cartesian coordinate variables; t is time; and ∇ is $[(\partial/\partial x)i + (\partial/\partial y)j + (\partial/\partial z)k]$. The term on the left hand side of equation (1) expresses the change in fluid mass contained in the void space of the local volume with time. The first term on the right hand side of equation (1) represents the contribution to local fluid mass change due to excess of fluid inflows over outflows. The second term (Q_p) accounts for external additions of fluid.

The fluid mass balance (equation 1) can also be represented by:

$$(\rho S_{op})\partial p/\partial t + [\varepsilon\partial\rho/\partial C]\partial C/\partial t - \nabla.[(\varepsilon\rho k/\mu).(\nabla p-\rho g)] = Q_p \quad \ldots(2)$$

where $S_{op} = [(1 - \varepsilon)\,\alpha + \varepsilon\,ß]$ is specific pressure storativity; α is porous matrix compressibility; ß is fluid compressibility; C is solute mass fraction or mass of solute (M_s) per mass of fluid (M_s/M); k (x,y,z) is solid matrix permeability tensor; μ(x,y,z,t) is fluid viscosity, p (x,y,z,t) is fluid pressure, and g is the gravity vector.

Conservation of mass of solute

The solute mass balance for a single species stored in solution is expressed as:

$$\partial(\varepsilon\rho C)/\partial t = -\nabla.(\varepsilon\rho VC) + \nabla.[\varepsilon\rho(D_m I + D).\nabla C] + Q_p C^* \quad \ldots(3)$$

where D_m is apparent molecular diffusivity of solutes in solution in a porous medium; I is the identity tensor (dimensionless); D is the dispersion tensor; and C^* is the solute mass fraction of fluid sources (M_s/M). The term on the left hand side of equation (3) expresses the change in solute mass with time in a volume due to mechanisms represented by terms on the right hand side. The first term on the right hand side of equation (3), involving fluid velocity (V), represents advection of solute mass into or out of the local volume. The second term, involving molecular diffusivity of solute (D_m) and dispersivity (D), expresses the contribution of solute diffusion and dispersion to the local changes in solute mass. The diffusion contribution is based on a physical process driven by concentration gradients, and is often negligible at the field scale. The last term accounts for dissolved-species mass added by a fluid source with concentration C^*.

SUTRA simulation is based on a hybridisation of finite-element and integrated finite-difference methods employed in the framework of a method of weighted residuals. The method is robust and accurate when employed with proper spatial and temporal discretization. Standard finite-element approximations are employed only for terms in the balance equations which describe fluxes of fluid mass, solute mass and energy. All other non-flux terms are approximated with a finite-element mesh version of the integrated finite-difference methods.

Data Requirement

The most essential types of data required are salinity records with depth in a number of observation wells, hydro-dispersive parameters (or atleast detailed description of lithology, by which estimates of hydraulic conductivity can be made from similar type of areas), and tidal lags and heights at various points in the region of interest. It is also necessary to have recharge information. This involves not only the knowledge of rainfall but also how much of it enters the groundwater system and how much is drawn off by vegetation. Other useful information would include an accurate topographic map, a land use map, water supply data including extraction data, local knowledge and experience, and estimates of expected changes in regional rainfall patterns.

Two SUTRA data files are required: (i) SUTRA input data and (ii) initial conditions of pressure and concentration or temperature for the simulation. Re-programming of subroutines BCTIME and UNSAT is required to implement time-dependent boundary conditions and unsaturated flow functions, respectively. A graphical postprocessor, SUTRA-PLOT, developed by Souza (1987) is available for use with SUTRA. This postprocessor facilitates interpretation of the simulation results.

The Study Area

The study area (Figure 1) lies in the Ernakulam district of Kerala (India). Ernakulam district is situated in the middle of state bounded by Trichur district in the North, Idukki district in the East, Kottayam and Alleypy districts in the South and by Lakshadweep Sea in the West. The area of the district is 2408 sq. km. It lies between North latitudes 9^0 42’ and 10^0 18’ and East longitudes 76^0 9’ and 77^0 2’.

Physiographically, Ernakulam district can be divided into three well defined areas viz. the coastal plains in the West, the middle region in the center and the hilly ranges in the small areas in North-East and South-East parts of the district. The ‘Coastal Plains’, covering an area of 1726 sq. km. has elevation less than 6 m above Mean Sea Level (MSL), parallel to the coast. The width of the coastal plains generally ranges from 10 km – 15 km. Coastal alluvial soils as well as laterites cover the area parallel to the coast dominated by the presence of number of backwater channels. The selected area for the present study lies in this region.

Wet type of climatic conditions prevails in Ernakulam district. The normal rainfall ranges from 2698.9 mm to 5883.5 mm per annum. On an average, 3000 mm rainfall occurs annually in the district. Out of this, the major contribution is from South-West monsoon season and other seasons contribute less rainfall. The maximum rainfall occurs during the period from June to September. The mean wind speed ranges from 6.7 km/h to 10.9 km/h. The relative humidity is higher (76% – 79%) during monsoon months, i.e., from June to October. In rest of the year, it ranges from 66% - 70%. The temperature is pleasant during the entire months in a year. The maximum temperature ranges from 28.1^0C to 31.4^0C and the minimum temperature ranges from 23.2^0C to 26.0^0C. The average annual maximum temperature is 29.8^0C and the minimum temperature is 24.4^0C. Generally March to May months are hottest and November, December and January months are coldest. Lithology of Ernakulam district is presented below.

Age	Formations	Lithology
Recent	Alluvium	Sands
Sub-recent	Laterite	Laterite derived from tertiary sediments
Tertiary	Quilon beds	Limestone, calcareous clay, lateritic clay

The unconsolidated alluvial formations occupy most of the area on the coastal plains in the western parts of Ernakulam district. It is of recent origin. It includes the sediments of backwaters and fine to medium green quartzite sand, silty sands of the plains and grey to dark grey beach sands. The porosity of sand in this region is 0.4 – 0.5. They are excessively drained with very high hydraulic conductivity of 65 m/day. The laterite formations occur all along the midland region and adjacent to the alluvium in the coastal plains. Laterite is formed due to the weathering of either crystalline or sedimentary rocks. These are porous, reddish brown to buff coloured. The porosity of laterite formations ranges from 0.27 – 0.3 and the hydraulic conductivity is 30 m/day. Quilon beds are present below the laterite formations. It is composed of calcareous clay and lateritic clay. It is having very less porosity ranging from 0.15 – 0.2 with the hydraulic conductivity of 10 – 15 m/day. The geological section across study area is shown in Figure 2.

The groundwater occurs in phreatic conditions in weathered and fractured crystalline rocks, lateritic and coastal sediments. It occurs under semi-confined to confined conditions in the deep-seated fractured aquifers of the tertiary sediments. The alluvial beds in Ernakulam district are represented by backwater and lagoonal deposits brought down by the West flowing rivers. These deposits comprise pure white quartz sand, dirty white silt and silty sand, grey to dark grey beach sand and red Terri sands. The alluvium forms a potential phreatic aquifer and is extensively developed by large number of dug wells and filter point wells to meet domestic and agricultural needs.

In areas, where surface water is not available, drinking water requirement is met from groundwater sources through dug wells, bore wells and tube wells constructed by Kerala Water Authority. There are a total of 60 dug wells having an average dimensions of 3 m diameter and 10 m depth with an average pumping of about 6 - 8 hours per day. The wells are fitted with 5 – 10 HP pumps. The population served ranges from 500 – 10,500. There are a total of 45 bore wells in the district. The bore wells are between 50 – 80 m depth and have discharge ranging from 0.2 - 9.25 lps. The wells with higher discharges are fitted with pumps of 5 – 15 HP motors; low yielding wells are fitted with hand pumps. A population of 1300 to 11,000 is served by each well.

Simulation of Seawater Intrusion in Ernakulam Coast

The seawater intrusion in a section of Ernakulam coast was simulated using SUTRA. Study area map, rate of groundwater recharge (considered as a percentage of rainfall), depth to water table, groundwater draft and location of wells were collected from Central Groundwater Board, Kerala region, Thiruvananthapuram. Tidal data were collected from National Institute of Oceanography, Ernakulam. The model was calibrated by varying the relevant parameters and applying appropriate boundary conditions. The latest version of SUTRA i.e. V09972D was used for the simulation. The following sections present the analysis and results.

Discretization and Boundary Conditions

For the simulation of seawater intrusion in a part of Ernakulam coast, a vertical section of the aquifer along the line A-B (as shown in Figure 1) has been considered. The length of the section was assumed as 2500 m. The depth of section is upto the depth of bedrock, which is equal to 90 m below MSL. The top layer is of sand, which extends upto a depth of 10 m. Below this layer, laterite is present upto 80 m from MSL and the bottom layer comprises of lateritic clay. The thickness of the section for the simulation has been assumed as 1 m. The vertical section has been discretized considering the rectangular element size of 100 m $\times$ 5 m. The number of elements in X and Y directions have been considered as 25 and 18 respectively. Therefore, total number of elements and nodes considered are 450 and 494 respectively.

A no-flow boundary condition has been specified along the bottom of the mesh at a depth of 90 m where the bedrock is considered to be impervious. A recharge boundary due to rainfall has been specified at the top of the aquifer. Along the left vertical boundary, a hydrostatic pressure defined by,

$$p = \rho_s g d \qquad \ldots(4)$$

has been imposed. Here, p is the hydrostatic pressure $[M/(LT^2)]$, ρ_s is the density of seawater (M/L^3), g is the acceleration due to gravity (L/T^2), and d is the depth (L). Therefore, the pressure at the top of this left side boundary is zero and increases linearly with depth. The finite element mesh and boundary conditions are shown in Figure 3.

The boundary conditions for the transport simulation are dependent on the flow boundary conditions. The total dissolved solids (TDS) of recharge due to rainfall is zero (i.e. C* = 0 kg TDS/kg fluid). Any inflow, occurring through the specified pressure boundaries, has a sea water concentration of 35,700 mg/L TDS (i.e. C* = 0.0357 kg TDS/kg fluid). Any flow out of the mesh, at the specified pressure boundaries, occurs at the ambient concentration of the aquifer fluid. Solute may neither disperse nor advect across the no-flow boundary.

Calibration and Model Parameters

The effect of seawater tides was incorporated in the simulation runs. The tidal signal is manifested as a pressure wave that propagates inside from the coastal boundary. As it propagates, it weakens with distance and time. Sinusoidally varying pressures were applied at the sea boundary. The amplitude of sine wave function (assumed for seawater tides) was taken as 0.3 m with frequency of 2 cycles per day. Subroutine BCTIME was modified in the program USUBS.FOR of SUTRA, to set time dependent specified pressures.

In view of minor groundwater draft in the study area, the section has been assumed to be in a steady state condition. To obtain steady state solution, the simulation runs were made for 4500 time steps of 15 days each which corresponds to a total simulation period of about 185 years. After this period, the profiles are apparently similar in all respects indicating that the steady state condition has reached.

Salinity measurements were available for only two observation wells (indicated as 1 and 2 in Figure 1) along the section. First observation well is located at 331 m from high tide line with salinity measured as 650 mg/l at 2.2 m below MSL. Second observation well is located at 484 m from high tide line with salinity measured as 253 mg/l at 3.0 m below MSL. The salinity values were computed by multiplying the electrical conductivity values by a factor of 0.69. Some of the parameters were assigned constant values in the simulation, as given in Table 1.

Table 1: Constant Parameter Values

S. No.	Parameter	Value
1.	Fresh water density (ρ)	1000 kg/m^3
2.	Seawater density (ρ_s)	1025 kg/m^3
3.	Fluid viscosity (μ)	1×10^{-3} kg/ms
4.	Coefficient of fluid density change with concentration ($\partial\rho/\partial c$)	700 kg/m^3
5.	Seawater concentration	35700 mg/l
6.	Porosity (%) Sand Laterite Lateritic clay	 0.40 0.27 0.15
7.	Recharge rate (10% of average rainfall)	300 mm/year

Table 2: Calibrated Parameter Values for the Study Area

S. No.	Parameter	Range	Best Suited
1.	Horizontal Hydraulic Conductivity, K_h (m/day) Sand Laterite Lateritic clay	 30 – 85 25 – 70 10 – 50	 45 40 25
2.	Horizontal Permeability, K_h (m^2) Sand Laterite Lateritic clay	 $3.5431\times10^{-11} – 1.0038\times10^{-10}$ $2.9525\times10^{-11} – 8.2672\times10^{-11}$ $1.1810\times10^{-11} – 5.9051\times10^{-11}$	 5.3146×10^{-11} 4.7241×10^{-11} 2.9525×10^{-11}
3.	Anisotropic ratio (K_h/K_V)	20 – 60	50
4.	Longitudinal Dispersivity, α_L (m) Sand Laterite Lateritic clay	 20 – 160 15 – 150 10 – 135	 70 35 30
5.	Transverse Dispersivity, α_T (m) Sand Laterite Lateritic clay	 0.20 – 1.60 0.15 – 1.50 0.10 – 1.35	 0.70 0.35 0.30
6.	Molecular Diffusivity (m^2/sec)	$1\times10^{-9} – 1\times10^{-10}$	1.5×10^{-9}

Wide ranges of values for other model parameters were tested to determine the best-suited value. The best-suited values are those values at which the actual and computed salinities are matched.

The range for these parameters and the best-suited, obtained through calibration are given in the Table 2.

Salinity Contours

The SUTRA-PLOT program produces a graphical display of simulation results from SUTRA model. It was extensively used for calibrating the model parameters. But because of its inherent limitations, SURFER package was used to plot the final salinity contours. SURFER is an interactive menu driven graphics program that produces three-dimensional surface representations. From the output data file of final run (attainment of steady state condition), the salinity contours were plotted (Figure 4) which shows zones of fresh water, saline water and transition zone. As per EPA standards, water having less than 500 mg/l of TDS (0.0005 kg TDS/kg fluid) can be considered as fresh water.

It can be observed from Figure 4 that a major part of the coastal area (within 2 km from the sea) has already been affected by brackish water. The availability of fresh water is beyond 400 m at the top of saturated zone, which increases upto 2 km at the bottom (i.e. 90 m depth). Therefore, any groundwater development activity near the coastal area may significantly affect the fresh water availability in view of further inward movement of saline water. Proper planning and remedial measures are therefore needed to contain the intrusion of seawater.

Influence of Pumping

Due to increasing population, urbanization and industrialization in Ernakulam, the rate of groundwater draft is continuously increasing, which leads to heavy exploitation of the aquifer. When the aquifer is disturbed due to excess pumping, the saline water will move until a new equilibrium is achieved. As a consequence of which, the transition zone moves inwards, increasing the extent of seawater intrusion. To visualize this effect, three imaginary equal drafts were considered at the distances of 484 m, 1000 m and 1500 m from High Tide Line (HTL).

When a draft of 12 m^3/d was considered, the fresh water contour shifts from 2100 m to 2250 m at the bottom. Due to a draft of 20 m^3/d, fresh water contour moves from 2100 m to 2400 m at the bottom (Figure 5). At a pumping rate of 30 m^3/d, the fresh water contour extends beyond the section considered (i.e. 2500 m) at the bottom.

Model Sensitivity and Limitation

The model is very sensitive with respect to changes in hydraulic conductivity and recharge. Higher values of hydraulic conductivity facilitate intrusion of seawater, whereas increased recharge has the opposite effect, diluting saline water within the aquifer. The model is also sensitive to changes in porosity, anisotropy and dispersivity but less sensitive to changes in molecular diffusivity. The two-dimensional simulation of Ernakulam aquifer with SUTRA indicated its strength in providing stable solutions with relatively long time step of 15 days. However, from a practical standpoint, the results are constrained by the limitation of simulating a three-dimensional problem with a two-dimensional model. In spite of its two-dimensional nature, SUTRA can provide useful insight into the processes involved in seawater intrusion in coastal aquifers, upconing of the fresh water - saline water interface, and analysing the effects of various processes on fresh water lenses and their management.

Conclusion

Seawater intrusion was simulated in a part of Ernakulam coast (India) under steady state conditions through Saturated-Unsaturated TRAnsport (SUTRA) model. The application of SUTRA is very useful in those cases where a two-dimensional vertical cross-section adequately represents the groundwater system.

Simulation of seawater intrusion for the section considered in the study shows that the sensitive zone (salinity more than 500 mg/l) in this area is between 400 m to 2000 m from the high tide line. This means that groundwater in this zone is already contaminated due to saline water (total dissolved solid concentration above the standard limit). Hence, it is not suitable for potable use. Therefore, any groundwater development activity in the region needs to be carefully planned with remedial measures in order to contain the further intrusion of seawater.

If reasonably good data are available, numerical models such as SUTRA can be employed to provide an important means for guiding management decision. Observations of tidally-varying water levels and salinities in wells are more readily available than, for example, estimates of dispersivity. Realistic value of dispersivity can be achieved by matching model behaviour to well observations over a range of dispersivity values in a two-dimensional model. Hydrogeological parameters, thus estimated, can then be applied to problems such as response to sea level change or varying rainfall in a three-dimensional model.

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