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Saltwater intrusion process in a layered coastal aquifer system

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Abstract
Coastal regions are characterised by the interaction of land, sea and atmosphere. Therefore, sustainable management of coastal areas pre-supposes integrated management of coastal waters, coastal lands and coastal ecosystems. Among the various hydrological issues of the coastal regions, saltwater intrusion and associated problems draw special attention as it can disrupt the susceptible hydrogeological equilibrium of the coastal aquifer. Seawater intrusion in coastal aquifer may be viewed as a natural process that occurs by virtue of the density contrast between freshwater and salinewater. However, it is essential to maintain an acceptable spatial and temporal equilibrium of saltwater ingress in a coastal aquifer system. This demands quantitative understanding of the pattern of saltwater movement, mixing between fresh and salinewater, and the factors that influence such processes. Prognostic analysis of the problem by means of mathematical modelling (of flow and solute transport) can be of great use in investigating the processes. The study presented herein investigates the process of saltwater intrusion, bringing forth useful inferences on the process. Simulation of saltwater intrusion process is carried out in a multi-layered coastal aquifer system using the USGS finite element model, SUTRA. The model has been applied to the coastal aquifer system with varied boundary conditions as well as aquifer parameters, to study their sensitivities. Analysis of the extent and intensity of saltwater intrusion in the aquifer system vis-a-vis aquifer/ aquitard permeabilities, influx at the boundaries, and dispersivity of the medium has been presented.

INTRODUCTION

Coastal areas usually comprise of low lands with small gradients bordering estuaries/ sea. The economic significance of coastal regions requires no elaboration. Coastal deltas are major areas of grain production too. Since coastal areas are characterised by the interaction of land, sea and atmosphere, environmental management of coastal areas presupposes management of coastal waters, coastal lands and coastal ecosystems (*Carter, 1988*). Among the various issues appertain to coastal zones, problems associated with salinisation are of major concern to the hydrologists. The migration of saltwater into freshwater aquifers under the influence of groundwater development can be termed as *saltwater intrusion (Freeze and Cherry, 1979)*. Being the sole reliable source of water, coastal communities generally rely on groundwater. However, the hydrogeological equilibrium of the coastal aquifer that might have been established over long periods is highly vulnerable. For instance, lowering water table as a result of pumping or removal of coastal dunes may contaminate the coastal aquifer with salt water. Transport of saltwater is mainly due to advection and dispersion. Normally, the denser saline water forms a deep wedge that is separated from freshwater by a transition zone. Under un-perturbed conditions, the saline water body remains stationary, its position being defined by the freshwater potential and hydraulic gradient. When the aquifer is disturbed by activities like pumping, the salinewater body may gradually advance until the deeper saline wedge enters the wells affecting water quality. In order to initiate and implement preventive measures efficiently, it is required to assess the spatial and temporal extent of intrusion phenomenon and also the transient nature of the coastal aquifer system. Mathematical modelling of flow and solute transport is of great help in such investigations.

The *Ghyben-Herzberg relation,* on the nature of saltwater-freshwater interface in coastal aquifers, expresses the depth to the saltwater interface at a point as a function of groundwater head at that point in a homogeneous, unconfined aquifer with an inherent hydrostatic assumption *(Freeze and Cherry, 1979)*. Later, Henry (*1960*) presented a mathematical solution for the steady state case that includes dispersion. Reilly and Goodman (*1985*) presented the advances made in the investigations pertaining to saltwater-freshwater relationships in coastal aquifer systems. It is striking that finite element methods have been widely used in simulating steady state/ transient positions of saltwater front in confined as well as unconfined aquifer systems *(Lee and Cheng,1974; Huyakorn and Taylor 1976; Pinder and Gray 1977; Frind, 1982; Mahesha and Nagaraja,1996)*. Reilly *(1990)* employed modelling techniques in order to examine groundwater flow in layered coastal aquifers. Recently, Ashtiani et al. *(1999)* used SUTRA model to solve the mixed form of the variably saturated flow equation in order to analyse the effects of tidal fluctuations on seawater intrusion. Among the various models used in saltwater intrusion studies, the finite element simulation model SUTRA *(Voss, 1984*) is the most popular one (*Voss and Souza, 1987; Reilly, 1990; Griggs and Peterson, 1993; Narayan and Armstrong, 1995; Ghassemi et al., 1996; Kumar, 1998; Ashtiani et al., 1999*).

CONCEPTUALISATION

Seawater intrusion in coastal areas may be viewed as a natural process and poses no hazard to water quality until the equilibrium is disturbed. A sustainable groundwater development and management programme in coastal aquifers should therefore aim at (i) maintaining an acceptable spatial and temporal equilibrium of saltwater ingress in the aquifer system at a regional scale and (ii) ensuring quality standards in the pumped water. These objectives necessitate analysis of the saltwater intrusion problem at regional scale as well as at local/ point scale.

In the present study, a multi-layered coastal aquifer system has been modelled using the USGS finite element model for *Saturated-Unsaturated fluid density-dependant groundwater flow with energy TRAansport or chemically reactive single species solute transport*, SUTRA (*Voss, 1984*) for various boundary conditions and aquifer parameters. The saltwater intrusion profiles for steady-state/ transient conditions have been obtained for different cases across a vertical plane bordering the layered aquifer and the sea. The hypothetical layered coastal aquifer system visualised for the simulations is 100 m long and 50 m thick. The geometry of the aquifer system and boundary conditions are shown in Fig.1. The left-hand (land-ward side) inflow boundary has an evenly distributed mass flux, Q_{IN} with concentration, C_{IN}. The top boundary is a no-flow boundary making the set-up a confined aquifer system. The bottom of the aquifer system is an impermeable boundary. The right-hand boundary (sea-ward side) is at hydrostatic pressure with seawater. Water which enters the section through this boundary has concentration, $C_{BC} = C_s$ of seawater.

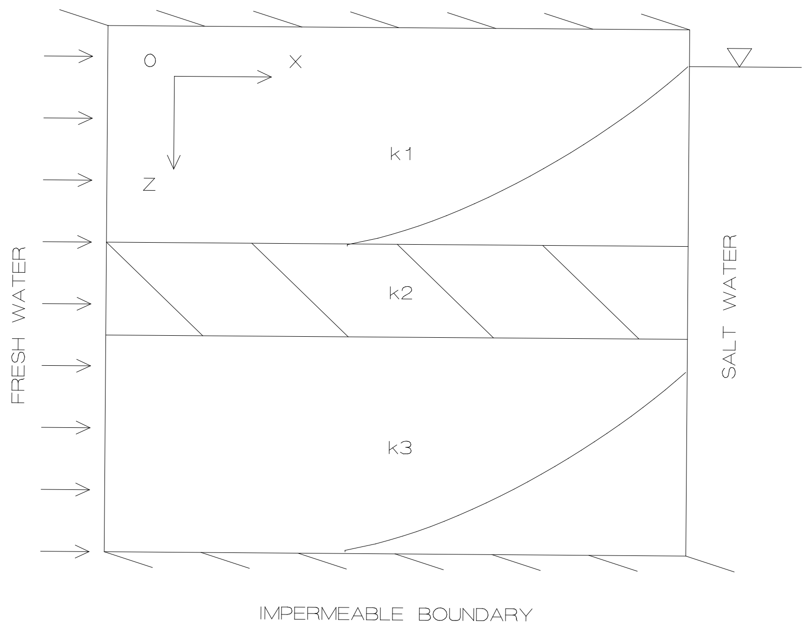


Figure 1. Cross-sectional sketch of the hypothetical coastal aquifer-aquitard system.

METHODOLOGY

The finite-element representation of the system is comprised of 1326 nodes and 1250 elements. The rectangular elements are all of the same dimensions, with sides 2 m x 2 m. A cross-sectional width of one metre is assumed. The coastal aquifer system is partitioned into a top and a bottom aquifer by the presence of an aquitard of thickness 10 m. Thus, the thicknesses of the top aquifer and bottom aquifer are 20 m each.

The seawater intrusion into the confined aquifer-aquitard system is a non-linear process and is solved by approaching the steady state situation gradually with a series of time steps. Different lengths of time steps, varying from 60 sec. to 1000 sec., have been used for simulations under transient conditions. Initially, the aquifer system is saturated with freshwater and there is no saltwater present in the system. At time t=0, saltwater begins to intrude the freshwater system by moving under the freshwater from the sea boundary; the intrusion being caused by the greater density of the salt water. The pressure, concentration and velocities are solved for each time step.

Model Description

SUTRA model is primarily intended for two-dimensional simulation of flow, and solute and energy transport in saturated and variable density systems. Simulation can be done in either areal plane or in a cross-sectional plane. The model uses a two-dimensional bi-linear Galerkin finite-element approximation in space and an implicit finite difference approximation in time to solve the governing equations. Parameter values of aquifer material, flow and transport may vary throughout the simulated region. Also, sources, boundary conditions of fluid, solute and energy may be specified to vary with time. Dispersion processes in the model include diffusion and two types of fluid velocity-dependent dispersion.

Governing Equations

The simulation of sea water intrusion requires the solution of partial differential equations that describe *conservation of mass of fluid* and *conservation of mass of solute (Voss and Souza, 1987).*

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

$$\frac{\partial(\varepsilon\rho)}{\partial t} = -\Delta\bullet(\varepsilon\rho V) + Q_p \qquad (1)$$

where ε is porosity; ρ is fluid density [M/L^3]; Q_p is fluid mass source [M/L^3T)]; V is fluid velocity [L/T]; t is time [T]; and L is [(M/Mx)i+(M/My)j+(M/Mz)k]. The term on the left hand side of equation (1) expressed 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 this equation represents the contribution to local fluid mass change due to excess of fluid inflows over outflows and the second term (Q_p) accounts for external additions of fluid. Density, ρ is represented as a linear function of the concentration, C.

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

$$\frac{\partial(\varepsilon\rho C)}{partialt} = -\Delta\bullet(\varepsilon\rho V C) + \Delta\bullet\left[\varepsilon\rho(D_m I + D)\bullet\Delta C\right] + Q_p C^* \qquad (2)$$

where D_m is apparent molecular diffusivity of solutes in the solution in a porous medium [LT^2/M]; I is the identity tensor [dimensionless]; D is the dispersion tensor [LT^2]; and C* is the solute mass fraction of fluid sources. The term on the left hand side of equation (2) 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 involving fluid velocity (V), on the right hand side of equation (2), 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 added by a fluid source with concentration C*. The mechanical dispersion tensor D is related to the velocity of ground water flow.

SIMULATIONS AND ANALYSIS

The transient nature of simulations, effect of permeability of the medium, influence of boundary conditions and dispersivity on saltwater intrusion profiles have been investigated using the finite-element model SUTRA. The influence of flow barriers of different permeabilities on the intrusion phenomenon in a layered coastal aquifer system is also analysed. The transient/ steady-state values of concentration, obtained through simulations, have been normalised by the saltwater concentration, C_s and then plotted as the isochlors. As such, the isochlors vary from 0.0 (freshwater) to 1.0 (saltwater).

A total simulation period of 10^6 seconds, consisting of 1000 time steps, was found to be sufficient for the process to reach steady-state situation. The left-hand inflow boundary has an evenly distributed mass flux, Q_{IN} (varying from 1kg/s to 8kg/s) with concentration, C_{IN}=0.0. The top boundary is a no-flow boundary which makes the set-up a confined system. The bottom of the aquifer system is an impermeable boundary. The right-hand boundary is at hydrostatic pressure of seawater through use of specified pressure nodes. Water which enters the section through these nodes has concentration, C_s=0.0357 kg(dissolved solids) per kg(seawater). The values/ range of values assigned to various parameters used in the simulations are given in Table 1. Also, the various cases simulated alongwith particulars are tabulated in Table 2. It may be noticed that the middle layer can act as a flow-barrier depending up on the permeability value assigned to it in the simulations.

Table 1. List of parameter values assigned in the simulations.

Parameter	Value(s)
Soil Porosity, ε	0.35 and 0.49
Soil Permeability, k	1.020408x10^{-9} m^2 to 1.020408x10^{-16} m^2
Saltwater Concentration, C_s	0.0357 kg(dissolved solids) / kg(seawater).
Saltwater Density, ρ_s	1025 kg/ m^2
Freshwater Density, ρ_0	1000 kg/ m^2
Density variation, $M\rho/MC$	700. [kg (seawater)^2 / kg dissolved solids. m^3]
Freshwater concentration, C_0	0. [kg (dissolved solids) / kg (seawater)]
Freshwater input rate, Q_{IN}	1 kg/s to 8 kg/s
Molecular diffusivity, D	6.6x10^{-6} m^2/s
Acceleration due to gravity, g	9.8 m/s^2
Thickness of the cross-section, B	1 m (assumed)
Dispersivities, $\alpha_L = \alpha_T$	1m to 10m
Simulation time, t	10^6 sec.

First of all, the transient nature of saltwater intrusion process is investigated (case-1). The intrusion profiles at the end of time periods 0.3 hours, 70 hours and 280 hours respectively are compared in Fig.2. The isochlor values shown in the figures are 0.02, 0.10, 0.25, 0.50, 0.75, and 0.90 respectively. Initially the profiles are vertical (Fig.2a) as the freshwater influx is yet to reach the seaward side of the cross-section. After 70 hours, freshwater discharge is established in the aquifer mostly through the top portion of the aquifer system and is clear from the inclined profiles (Fig.2b). At the end of 280 hours, traces of saltwater can be detected in the aquifer even half-way through the section (Fig.2c). The intrusion process was found to attain steady state by this time as further simulations with larger time periods did not yield any noticeable changes in the profiles.

The influence of permeability of the medium on the saltwater intrusion profiles in the aquifer system is examined in case-2. Soil porosity values used in case-2 (also for case-3, later) are, ε=0.35 and ε=0.49 for the aquifer and aquitard respectively. Freshwater input through the boundary is kept at the rate of 1 kg/s. The permeabilities of the layers (from top to bottom) are k_{T1}=1.02x10^{-10} m^2 , k_{M1}=1.02x10^{-12} m^2, and k_{B1}=1.02x10^{-9} m^2 corresponding to the profile shown in Fig.3a, wherin there is a saltwater intrusion zone in the top aquifer though the concentration is small. It can be seen that, the intrusion zone in the bottom aquifer spreads beyond half-way in the cross-section. Profiles of Fig.3b are generated with permeabilities smaller by one order of magnitude (compared to that of Fig.3a) for the top and middle layers while keeping the permeability of the bottom layer same. It is seen that the intrusion zone in the top aquifer has vanished and full discharge of fresh water is established at the aquifer-sea boundary. There is, practically, little intrusion into the middle layer owing to the small permeability. Further, though the permeability of the bottom layer was not altered, the isochlors in the bottom aquifer have now retreated backwards. This is because of a decline in the solute movement from the upper layers to the bottom layer due to reduced connectivity and also due to lack of saltwater intrusion in the upper layers. It is, therefore, obvious that the saltwater intrusion profile in a deeper aquifer in a multi-layered system can be influenced not only by its own permeability but also by the permeabilities of layers above.

Table 2. List of various cases analysed using SUTRA for a layered coastal aquifer system.

Case	Plots	Description of investigation	Parameter values
1	Fig.2	Transient nature of saltwater intrusion profiles	t_1 = 0.30 Hrs., t_2 = 230 x t_1 t_3 = 920 x t_1
2	Fig.3	Effect of change in permeabilities of the layers on saltwater intrusion profiles	k_{T1}=1.02x$10^{-11}$$m^2$, k_{M1}=1.02x$10^{-13}$$m^2$, k_{B1}=1.02x10^{-9} m^2, k_{T2}=10 x k_{T1}, k_{M2}=10 x k_{M1}, k_{B2}=1 x k_{B1}
3	Fig.4	Effect of freshwater input rate on saltwater intrusion profiles	Q_1 = 8 kg/s Q_2 = 0.25 x Q_1
4	Fig.5	Influence of dispersivities on saltwater intrusion profiles	α_{L1}=α_{T1}=2m, α_{L2}=α_{T2}=4m, α_{L3}=α_{T3}=10m
5	Fig.6	Influence of aquitard permeabilities on saltwater intrusion profiles	k_{M1}=1.02x$10^{-10}$$m^2$, k_{M4}=1.02x10^{-12} m^2 k_{M6}=1.02x10^{-16} m^2

Case-3 explores the effect of changes in fresh water influx on the saltwater intrusion profiles in a layered aquifer system. The permeabilities of the top, middle and bottom layers, respectively are: k_T=1.02x10^{-9} m^2, k_M=1.02x10^{-13} m^2, and k_B=1.02x10^{-9} m^2. The profiles shown in Fig.4a and Fig.4b are obtained with freshwater injection rates of 8 kg/s and 2 kg/s respectively, through the left-hand boundary. When the rate of recharge in the aquifer system is high the saltwater intrusion zones in the top and bottom aquifers are confined to a small region as shown in Fig.4a. Having the same permeability values, the pattern of intrusion profiles in both the aquifers is similar. Profiles in Fig.4b are obtained with a reduced freshwater influx rate (one-fourth of that of Fig.4a). Four-times reduction in the freshwater injection rate facilitated the intrusion zone to progress further into the medium. A staggered transition-zone due to the presence of the flow barrier (aquitard) can also be observed. This demonstrates that decline in recharging of the aquifer by way of reduced river flows can propagate intrusion of saltwater further inside the aquifer system.

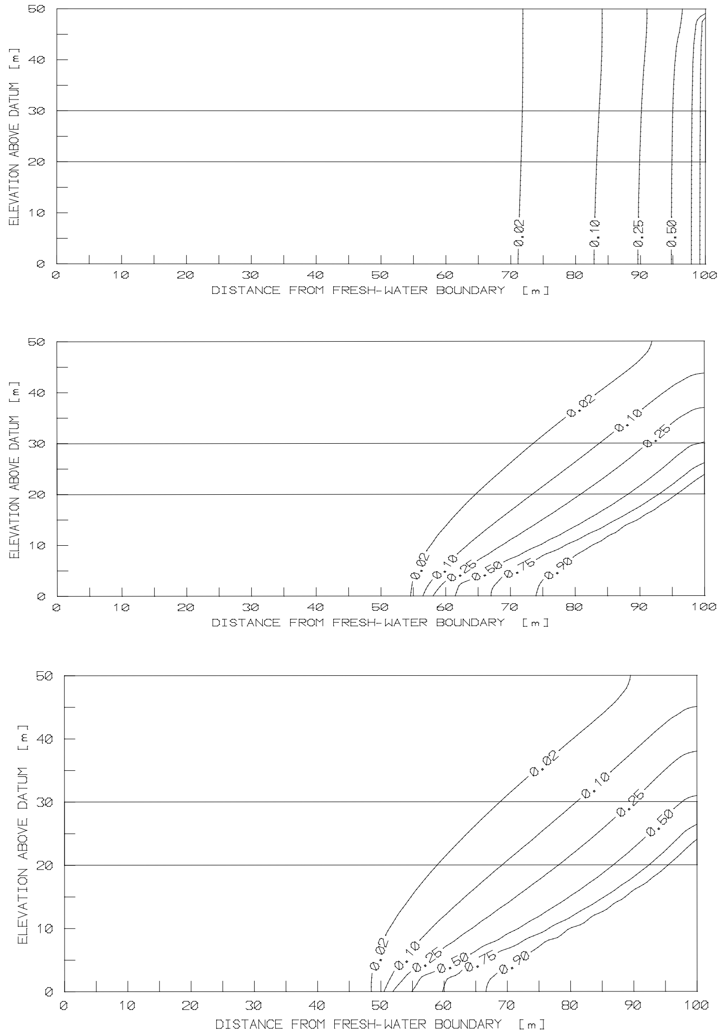
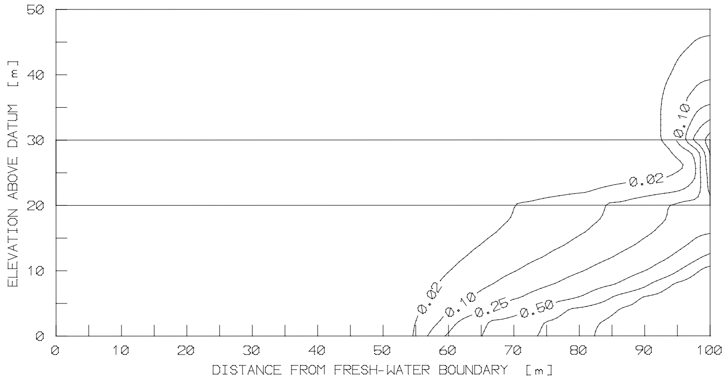


Figure 2. Transient profiles of saltwater intrusion in the cross-section with a uniform permeability (k=1.02x10^{-9} m^{2}) for all the layers; (a) profile after a simulation period of 0.30 hours, (b) profile after a simulation period of 70 hours and (c) profile after a simulation period of 280 hours.



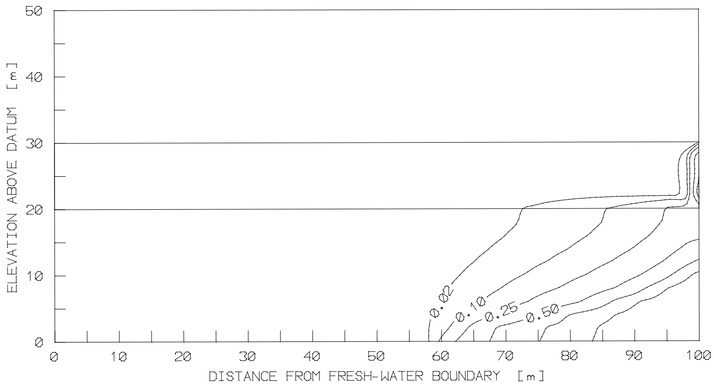


Figure 3. Effect of permeability on saltwater intrusion in a layered aquifer system; (a) Isochlors with permeabilities k_T=1.02x10^{-10} m^2 (Top), k_M=1.02x10^{-12} m^2 (Middle), and k_B=1.02x10^{-9} m^2 (Bottom) respectively, and (b) Isochlors with permeabilities k_T=1.02x10^{-11} m^2 (Top), k_M=1.02x10^{-13} m^2 (Middle), and k_B=1.02x10^{-9} m^2 (Bottom) respectively.

The behaviour of saltwater intrusion profiles, when different dispersivities are used for the process, are compared in case-4. The permeabilities of the layers are: k_T= k_B= 1.02x10^{-9} m^2 and k_M=1.02x10^{-12} m^2. Freshwater injection rate is 4 kg/s through the boundary. Since the layers are assumed to be homogeneous and isotropic, the longitudinal and transverse transmissivities can be identical for the simulations. Three dispersivity values viz., 2 m, 4 m, and 10 m have been used to get the saltwater profiles depicted in Fig.5a, Fig.5b, and Fig.5c, respectively. The spreading-out of the isochlors with increasing dispersivity values is quite discernible from the plots. With a dispersivity, $\alpha_{L1}=\alpha_{T1}$=2m the isochlors are concentrated in a zone near to the aquifer-sea boundary. Whereas, when the dispersivity, $\alpha_{L3}=\alpha_{T3}$=10m the isochlors are dispersed into the aquifer. It may be noticed that the increased dispersivity in the aquitard triggered larger mixing of the fluids and thereby more connectivity between the layers. After careful consideration of the grid dimensions and the range of aquifer parameter values, a dispersivity value of 2 m was found to be appropriate for the present simulations.

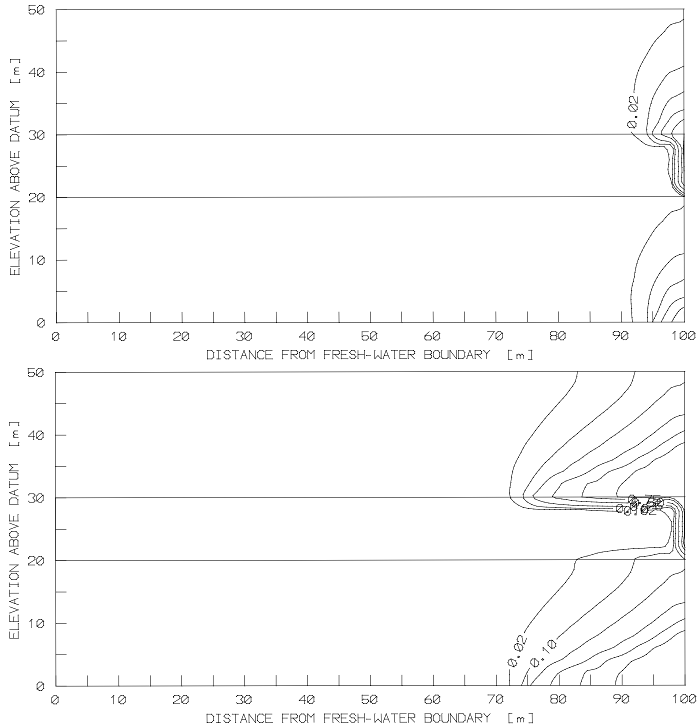


Figure 4. Effect of influx at the fresh-water boundary on saltwater intrusion in a layered aquifer system (k_T=1.02x10^{-9} m^2, k_M=1.02x10^{-13} m^2, and k_B=1.02x10^{-9} m^2); (a) Isochlors with fresh-water injection rate, Q_{IN}=8 kg/s, and (b) Isochlors with fresh-water injection rate, Q_{IN}=2 kg/s.

The transfiguration of saltwater intrusion profiles with the introduction of flow barriers of varying permeabilities is illustrated by means of the plots in Fig.6. Freshwater influx of 4 kg/s is applied at the land-ward boundary. Dispersivity for the medium is 2 m. The permeability values assigned for the flow barrier (aquitard) range from k_M=1.02x10^{-10} m^2 to k_M=1.02x10^{-16} m^2, while the permeability for the top and bottom layers is k_T=k_B=1.02x10^{-9} m^2. When the aquitard permeabilty (k_M=1.02x10^{-10} m^2) is one order of magnitude less than that of the aquifer, the isochlors are comparatively distortion-free (Fig.6a) indicating good connectivity between the layers. In subsequent simulations, the permeability of the aquitard has been reduced considerably. The change in pattern of intrusion profiles with reduced aquitard permeabilities may be visualised from Fig.6b and Fig.6c. Apparently, there is a gradual withdrawal of the intrusion zone in the medium associated with a reduction in the aquitard permeability. The extent of retreat of isochlors is more in the bottom aquifer as a result of reduced connectivity with the top aquifer, which in turn limits the solute movement from the top layer to the bottom layer. Comparing Fig.6b, for which k_M=1.02x10^{-12} m^2, with Fig.6c, for which k_M=1.02x10^{-16} m^2, shows that further reduction in the permeability of the flow barrier is not causing much changes in the intrusion profile. Thus, the presence or absence of a flow barrier in a coastal aquifer system can regulate the process of saltwater intrusion.

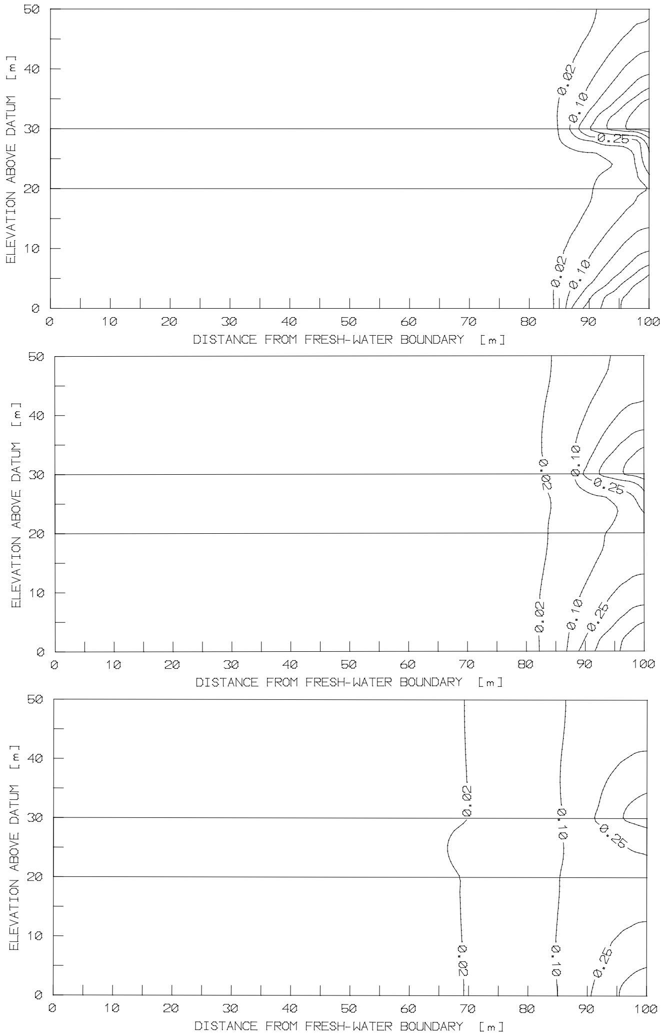


Figure 5. Effect of dispersivities on saltwater intrusion in a layered aquifer system (k_T=k_B=1.02x10^{-9} m^2, and k_M=1.02x10^{-12} m^2. Saltwater intrusion profiles with (a) α_L=α_T=2m, (b) α_L=α_T=4m, (c) α_L=α_T=10m.

In layered coastal systems, the scale of horizontal movement is usually different from the scale of movement through confining units. To reflect this difference in scale, material-dependent dispersivities may be used for the layers in the simulation (*Reilly, 1990*). Therefore, the influence of aquitard permeabilities on intrusion profiles were investigated with material-dependent dispersivity also. However, no changes were noticed in the resulting profiles. The reason could be due to the small lateral extent of the present simulation set-up, wherein the values of dispersivity can not vary largely in the aquifer and aquitard portions. So, it is felt that use of material-dependent dispersivities may be useful only in regional simulation of large multilayered coastal aquifer systems.

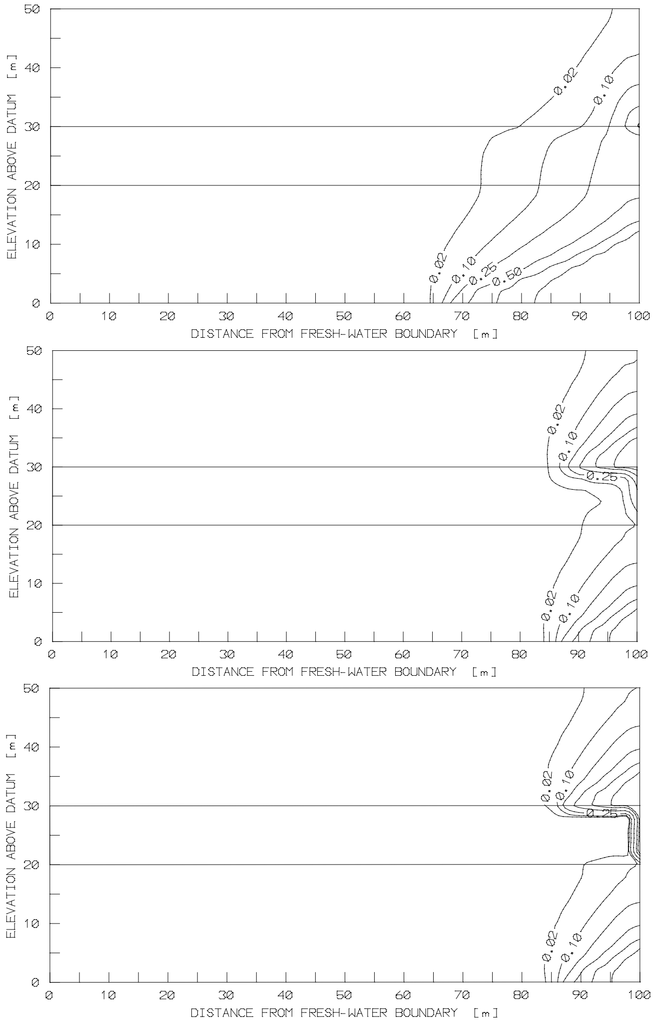


Figure 6. Saltwater intrusion profiles in a layered aquifer system with varying permeabilities for the confining layer. (a) Isochlors with permeability for the confining layer, k_M=1.02x10^{-10} m^2, (b) Isochlors with permeability for the confining layer, k_M=1.02x10^{-12} m^2, and (c) Isochlors when permeability for the confining layer, k_M=1.02x10^{-16} m^2.

CONCLUSIONS

Analysis of saltwater intrusion process at regional as well as local scale is necessary for the planning of remedial measures aimed at maintaining acceptable spatial and temporal equilibrium of saltwater ingress in coastal aquifers. It is showed that mathematical modelling of saltwater intrusion is a powerful tool for the purpose. A multi-layered coastal aquifer system has been simulated using the USGS finite element model SUTRA for different boundary conditions and aquifer parameters. The saltwater intrusion profiles for various scenarios have been obtained and analysed. Those include the influence of changes in the permeabilities of aquifers and aquitards, changes in flux at the boundaries, and changes in dispersivities in the medium on the intrusion profiles. Following conclusions can be drawn from the analyses: (i) Saltwater intrusion in a deeper aquifer in a multi-layered system can be influenced not only by its own permeability but also by the permeabilities of layers above; (ii) A decline in the recharge of a coastal aquifer triggers intrusion of saltwater deeper inside the aquifer system; (iii) The presence of a flow barrier in a coastal aquifer system can prevent the advancement of intrusion of saltwater deeper into the system; (iv) Use of material-dependent dispersivities do not produce significant improvements in local/ point scale simulations.

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