A New Focus on Groundwater–Seawater Interactions
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Numerical modelling of saltwater–freshwater interaction in the Walawe River basin, Sri Lanka

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Abstract A finite difference model that simulates freshwater and saltwater flow separated by a sharp interface has been applied to estimate the salinity intrusion in the lower part of the Walawe River basin to the southern coastal aquifer, Sri Lanka. The effect of hydrogeological factors on the dynamics of the freshwater–saltwater interface has been considered through storage coefficients, porosity and hydraulic conductivity. The paper concludes that hydraulic conductivity is the main hydrogeological factor affecting the movement of the freshwater–saltwater interface, and the saltwater intrusion is more sensitive to groundwater recharge than hydrogeological properties. Therefore, the model was calibrated by adjusting the hydraulic conductivity to match the observed salinity profile in the southern coastal aquifer. Simulation results compare well with the observed long-term salinity profile suggesting that the numerical model can be used to successfully simulate the salinity profile in the area.

Key words salinity intrusion; coastal groundwater resources; hydrogeology; southern coastal aquifer Sri Lanka

INTRODUCTION

Use of coastal aquifers as operational reservoirs in water resources systems requires the development of tools that make it possible to predict the behaviour of the aquifer under different conditions. Estimations of the freshwater–saltwater interface either in steady or transient conditions have become necessary in designing and planning of groundwater systems in coastal areas. Quantitative understanding of the patterns of movement and mixing between freshwater and saltwater, and the factors that influence these processes, are necessary to manage the coastal groundwater resources (Ranjan *et al.*, 2006).

In nature a freshwater–saltwater interface seldom remains stationary. Changes in aquifer stresses result in the movement of the interface. The main objectives of this study are to use a numerical model to understand the behaviour of the freshwater–saltwater interface and to evaluate the effects of different hydrogeological settings by applying the model to the lower part of the Walawe River basin in the southern coastal aquifer in Sri Lanka, which faces scarcity of fresh groundwater resources due to saline intrusion.

Modelling of the dynamics of the freshwater–saltwater interface

Many models have been developed to represent and to study the problem of saltwater intrusion. They range from relatively simple analytical solutions to complex numerical models. The first concept of the freshwater–saltwater interface, now widely cited as the Ghyben-Herzberg principle (Reilly & Goodman, 1985), is based on the hydrostatic equilibrium between fresh and saline water. After the introduction of the Ghyben-Herzberg principle, several analytical and numerical solutions were developed to describe the phenomenon. The movement of fresh groundwater and saltwater in coastal aquifer systems has been studied using two different approaches (Reilly & Goodman, 1985). In the first approach, freshwater and saltwater are assumed completely immiscible and a sharp interface exists between these two phases. In the other approach, the freshwater and saltwater are allowed to mix in response to flow and dispersion mechanisms within the aquifer.

The sharp interface models which solve the coupled freshwater and saltwater flow equations have been developed with different numerical techniques (Shamir & Dagan, 1971; Vappicha & Nagaraja, 1976). A finite element solution with an indirect toe tracking technique was presented by Wilson & Costa (1982). Polo & Ramis (1983) discussed an unconditionally convergent finite difference approach to solve the sharp interface problem. A sharp interface model which solves the coupled freshwater and saltwater flow equations has been developed and it was successfully applied to evaluate multilayered aquifer systems (Essaid, 1986, 1990).

MATHEMATICAL DEVELOPMENT OF SHARP INTERFACE MODEL

Sharp interface models couple the freshwater and saltwater flow equations based on the continuity of flux and pressure. In this approach, together with the Dupuit approximation, for each flow domain the equation of continuity may be integrated over the vertical direction to produce the following system of differential equations (Bear *et al.*, 1999):

$$\frac{\partial}{\partial x}\left[K_{fx}\left(h^f-h^i\right)\frac{\partial h^f}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{fy}\left(h^f-h^i\right)\frac{\partial h^f}{\partial y}\right]+q_f=S_f\frac{\partial h^f}{\partial t}-\theta\left[\left(1+\delta\right)\frac{\partial h^s}{\partial t}-\delta\frac{\partial h^f}{\partial t}\right]+\alpha\theta\frac{\partial h^f}{\partial t} \tag{1}$$

$$\frac{\partial}{\partial x}\left[K_{sx}\left(h^i-z^b\right)\frac{\partial h^s}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{sy}\left(h^i-z^b\right)\frac{\partial h^s}{\partial y}\right]+q_s=S_s\frac{\partial h^s}{\partial t}+\theta\left[\left(1+\delta\right)\frac{\partial h^s}{\partial t}-\delta\frac{\partial h^f}{\partial t}\right] \tag{2}$$

The location of the interface elevation is given by:

$$h^i=\frac{\rho_s}{\rho_s-\rho_f}h^s-\frac{\rho_f}{\rho_s-\rho_f}h^f \tag{3}$$

where ρ_f and ρ_s are specific weight in fresh and salt water, respectively, h^f and h^s are the piezometric heads of freshwater and saltwater regions, q_f and q_s are the flow rates in the fresh and salt water, respectively, and K_f and K_s represent the hydraulic conductivity in the fresh and salt water regions. Storage coefficients in the fresh and salt water regions are given by S_f and S_s respectively, θ is the porosity of the aquifer media. $\alpha = 1$ for an unconfined aquifer and $\alpha = 0$ for a confined aquifer.

Numerical scheme

Except for very simple systems, analytical solutions of those two coupled nonlinear partial differential equations are rarely possible. A numerical method must be employed to obtain approximate solutions. From equations (1) and (2), it is possible to derive a numerical model using implicit finite difference techniques. The continuous system described by the above two equations are replaced by a finite set of discrete points in space and time, and the partial derivatives are replaced by terms calculated from the differences in both freshwater and saltwater head values at these points. Spatial discretization is achieved using a block centred finite difference grid which allows for variable grid spacing. Fortran 77 computer code has been used for the modelling.

EVALUATION OF THE EFFECT OF HYDROGEOLOGICAL FACTORS

To investigate the effect of hydrogeological factors on the dynamics of the freshwater–saltwater flow systems, a 2 km × 2 km horizontal strip of an unconfined aquifer has been simulated by changing the hydrogeological properties. The effect of the specific storage was evaluated by increasing the storage coefficient by orders of magnitude. It shows that the changes in storage coefficient do not affect the location of the interface. The system responds in almost the same manner for different specific storage values. Porosity is the other factor which illustrates the storage of the aquifer. To investigate the effect of porosity on the behaviour of the flow system, porosity was changed from 0.1 to 0.4 in increments of 0.1 and the variation of the freshwater–saltwater interface has been checked. The change in porosity does not lead to a change in the position of the interface, but it leads to a change in the time period to achieve the steady state of the interface. Figure 1 shows the time taken to achieve the steady state interface at 500 m from the coastline. Reduction in porosity accelerates the movement of the interface and it drives the system to steady state over a shorter time period.

Hydraulic conductivity is the other factor which affects the change of the freshwater–saltwater interface. The hydraulic conductivity was changed over the range of

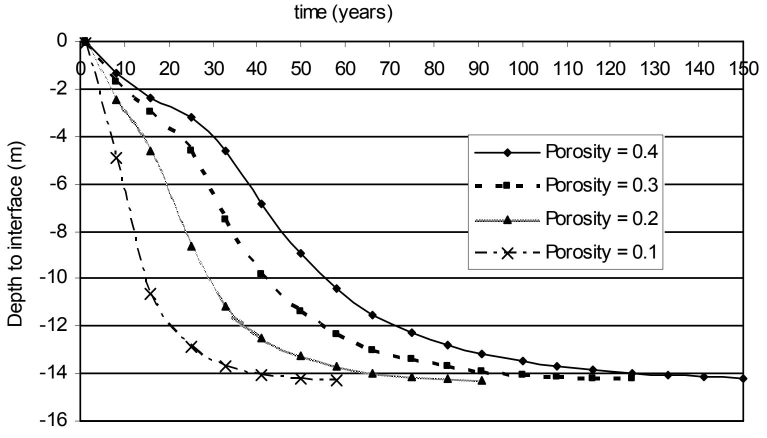

Fig. 1 Effect of porosity on the steady state of the interface.

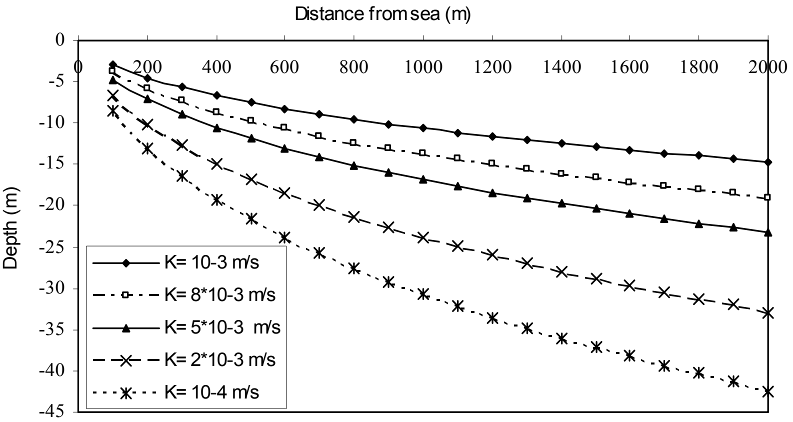

Fig. 2 Change in the interface with hydraulic conductivity (*K*).

10^{-3} m/s to 10^{-4} m/s. Figure 2 explains that the changes in hydraulic conductivity have an impact on the steady position of the interface. A change in hydraulic conductivity changes the transmissivity and it affects the head gradients necessary to maintain the freshwater flux. This process showed that the model is more sensitive with respect to changes in hydraulic conductivity than other hydrogeological factors.

Simulation of the effect of recharge

The effect of recharge on the dynamics of the freshwater–saltwater interface can be understood most readily by considering a simple, finite groundwater flow system in which all discharge flows to the ocean. Different groundwater recharge values have been simulated without changing the hydrogeological parameters to observe the change of interface. Figure 3 shows the variation of the steady interface with groundwater recharge. It shows that higher recharge can reduce saltwater intrusion. Saltwater will intrude farther inland unless the additional recharge can push the seawater equilibrium surface seaward.

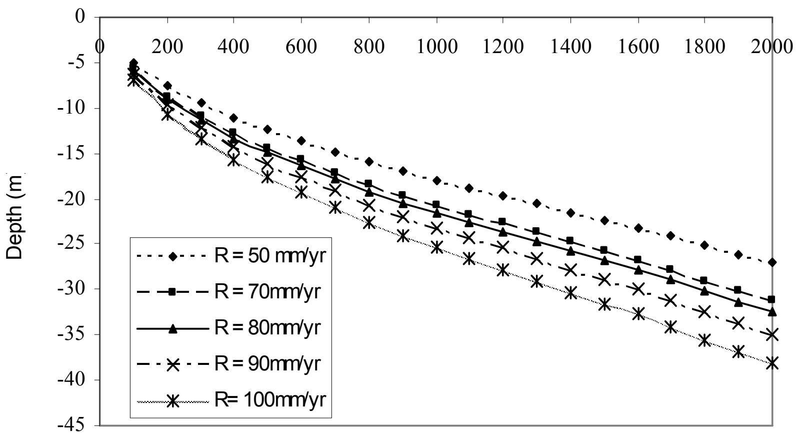

Fig. 3 Change in the interface with groundwater recharge.

APPLICATION TO SOUTHERN COASTAL AQUIFER

To compare the simulated interface with the observed salinity profiles, field data has been collected from the lower part of the Walawe River basin located in the southern coastal aquifer which is in the southern part of Sri Lanka (Fig. 4). The coastal plain, covering a major part of southern Sri Lanka, and has elevations less than 6 m above mean sea level (AMSL), parallel to the coast (Engineering Consultants, 1995). The width of the coastal plain generally ranges from 2 to 10 km. Coastal alluvial soils as well as laterites cover the area parallel to the coast. It includes river sediments and fine to medium green quartzite sand and beach sands (Statkraft Groner, 2000). Groundwater within the area is constrained by the unconsolidated alluvial and deltaic sediments, which were deposited by the main rivers and their distributaries (Kulathunga, 1998).

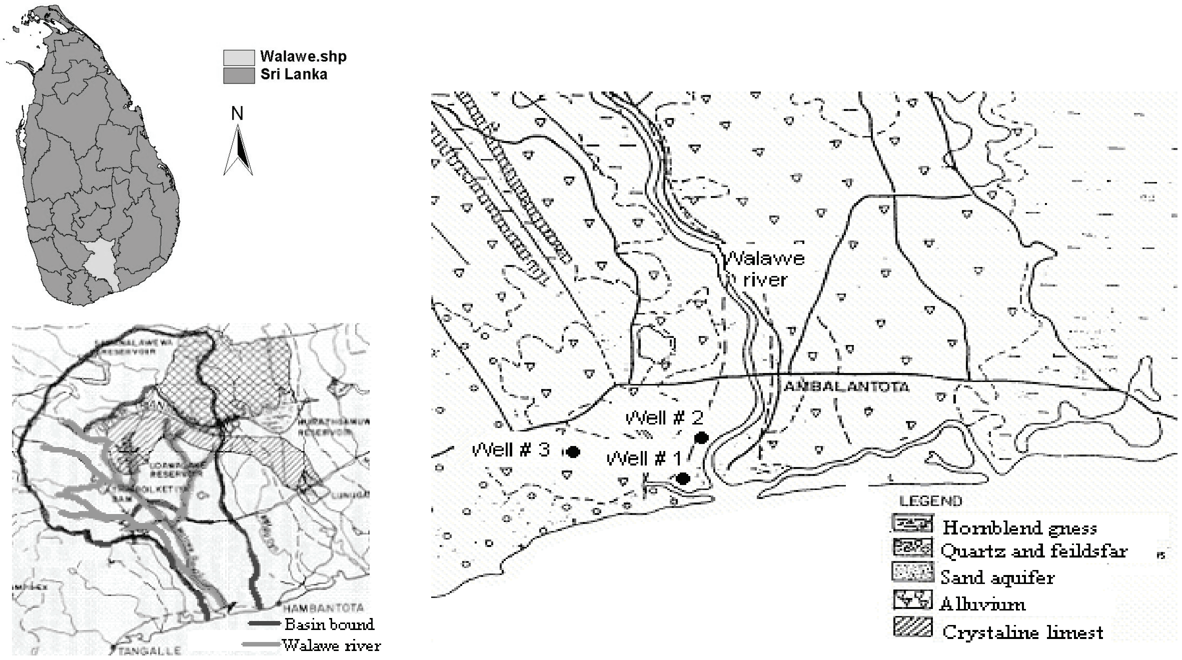

Fig. 4 Observation well locations in the lower part of Walawe River basin.

Calibration and verification of the model using field observation

Three observation wells have been used to measure the change in salinity profile in the area. The observation wells selected were at different distances from the coastline. As the salinity profile shows frequent changes in salinity intrusion, the observation wells were selected to a distance of 2 km from the coastline for the calibration and verification of simulated results. Well #1 is around 400 m from the coast. Well #2 and well #3 are 1 km and 2 km landward from the coast, respectively. Groundwater salinity was measured using the salinity meter, WQC-24. Weekly salinity measurements were measured during the period of investigation (September 2003–November 2004). Observation of a sharp interface is rarely encountered in the field. Literature studies show that the 50% salinity contour is the best representation of the sharp interface between saltwater and freshwater regions (Mahesha & Nagaraja, 1996; Scot & Stephen, 1998; Masciopinto, 2006). Therefore, we assume the 50% seawater salinity contour as equivalent to the sharp interface and depth to the freshwater–saltwater sharp interface was estimated using the vertical salinity profiles of observation wells.

Model calibration

The study area has been simulated as a single-layer unconfined aquifer, with the bottom defined by the position of the granite bedrock. The sharp interface model developed has assumed homogeneous aquifer properties. Since the southern coastal aquifer is not under any major stress such as extensive pumping, it has been assumed as steady until the change in groundwater recharge disturbs the system. On the sea side model boundary, a hydrostatic pressure was imposed where pressure is zero at the sea surface. The average annual groundwater recharge in the Walawe River basin has been estimated as 80 mm/year (Ranjan *et al.*, 2002). This has been used as a realistic value to represent the groundwater recharge in Walawe basin and the simulation runs were conducted with recharge value of 80 mm/year to generate the steady state condition. To calibrate the model for the initial steady state condition, the average elevation of the observed freshwater–saltwater interface in the first three months of the observation period was considered. The average depth to the sharp interface was estimated as 13.5 m at well #1; 21.5 m at well #2; and 34 m at well #3.

For the calibration process, a wide range of values for each parameter have to be tested to estimate the most suitable value. Since the hydraulic conductivity is the main hydrogeological factor affecting the movement of the salinity interface, the model was calibrated by adjusting hydraulic conductivity values to match the simulated steady interface location and the observed interface. The hydraulic conductivity varies across the area. The estimated hydraulic conductivity varies over a large range. The hydraulic conductivity of the southern coastal aquifer has been estimated using the available pumping test results and bore-hole data (Jayaweera, 2001; JICA, 2003). Aquifer materials and their deposition were observed from bore-hole data and relevant hydraulic conductivities were assigned. Since the coastal plain consists of river sediments and coastal alluvium, hydraulic conductivity is estimated to vary between 10^{-4} m/s to 10^{-3} m/s (Freeze & Cherry, 1979). Varying the aquifer properties, several model runs were carried out to find the most reliable location for the steady state salinity intrusion profile. The best fitting profile with the field observation data is shown in Fig. 5.

Verification of the model

The calibrated model has been used to verify the short-term changes in the freshwater–saltwater interface. Output from the steady state results was used as the initial condition to simulate the effects of realistic short-time changes in groundwater recharge on the system. During the model verification period, model coefficients obtained from the calibration process were kept as constants.

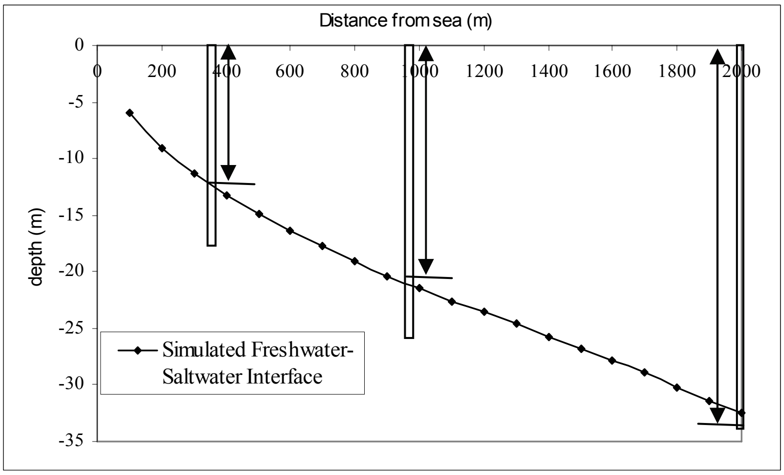

Fig. 5 The best fitting profile of the field observation with calibrated model results.

Since groundwater recharge is the main stress for short-term variations of the freshwater–saltwater interface, seasonal changes in groundwater recharge were assigned to the model. Monthly average groundwater recharge has been estimated using the water balance approach with meteorological data obtained from International Water Management Institute (IWMI) database for the Walawe benchmark basin. Estimated groundwater recharge shows that Walawe basin recharges in two seasons per year; the southwest monsoon season in October–December and the northeast monsoon season in April–June. Groundwater recharge is zero in the other months.

Continuous short-term observations (weekly) are available for well #1 and well #2. These observed weekly average salinity profiles from January 2004 to November 2004 have been used to verify the calibrated model. Figure 6 shows the comparison of weekly variation of the sharp freshwater–saltwater interface in observation wells #1 and #2 and the simulated monthly averaged interface using the sharp interface model.

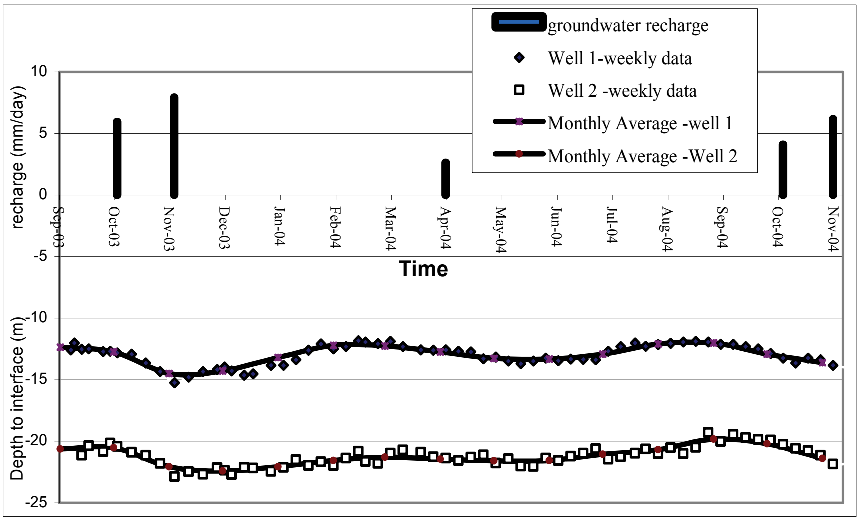

Fig. 6 Weekly variation of the sharp freshwater–saltwater interface.

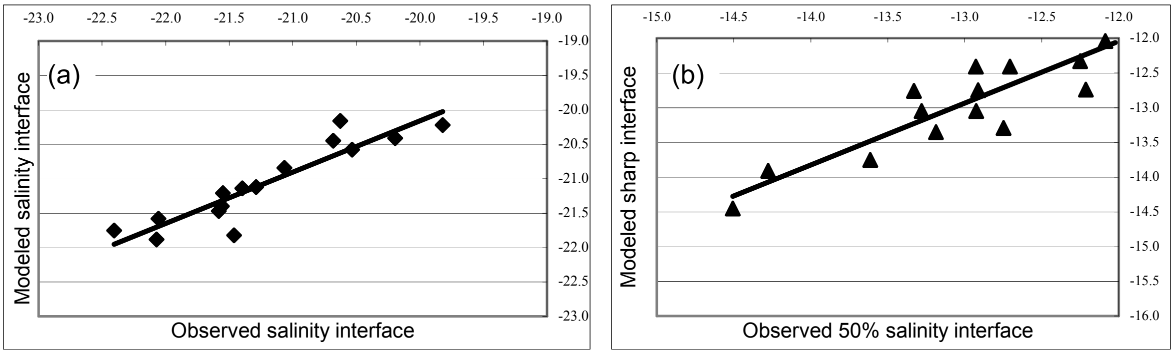

Fig. 7 Comparison of observed and modelled interface: (a) at well #1, (b) at well #2.

The correlation between simulated and monthly averaged observations is shown in Fig. 7. Correlation coefficients between model results and field observations for wells #1 and #2 were 0.86 to 0.77, respectively. These correlations verify a good agreement between model results and field observations.

This kind of simulations shows that numerical models can be used to reproduce the salinity profile in complex hydrogeological settings. It also indicates that any groundwater development activity in the southern coastal aquifer needs to be carefully planned with remedial measures in order to prevent the further intrusion of seawater.

CONCLUSIONS

The accurate solutions of the coupled, nonlinear partial differential flow equations require the utilization of a numerical technique. The sharp interface model developed has been applied to the lower part of the Walawe River basin in the southern coastal aquifer, Sri Lanka. Evaluation of the effect of hydrogeological factors on the dynamics of the freshwater–saltwater interface concluded that hydraulic conductivity is the main hydrogeological factor affecting the movement of the salinity interface. The simulation for groundwater recharge shows that saltwater intrusion is more sensitive to groundwater recharge than hydrogeological properties. Higher values of hydraulic conductivity facilitate intrusion of seawater, whereas increased recharge has the opposite effect. The numerical model was calibrated by adjusting the hydraulic conductivity to match the observed salinity profile in the southern coastal aquifer. The simulation has been carried out for September 2003 to November 2004, considering the changes in groundwater recharge. The observed short-term salinity profiles have been compared with the simulation results. The short-term variation of the salinity interface according to the changes in groundwater recharge shows that the comparison is in reasonable agreement. We conclude that the developed model is able to simulate the changes of the salinity profiles realistically and can be used to address the counter measures to prevent the salinity intrusion in Walawe River basin.

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