A conceptual model based on the sharp interface assumption was considered to estimate the change in the freshwater-saltwater interface. The model was used to evaluate the effect of geo-hydrological factors affecting the dynamics of freshwater-saltwater interface. The effect of storage coefficient, porosity and the hydraulic conductivity was mainly evaluated. Since the storage coefficient and the porosity are not much affecting the change of interface, the model was calibrated by adjusting the hydraulic conductivity to match the observed data in the coastal aquifer in lower part of the Walawe river basin, Sri Lanka. The simulation has been carried out for a range of recharge values. The results show that the saltwater intrusion is far more sensitive to recharge than aquifer properties.

**INTRODUCTION**

The use of coastal aquifers as operational reservoirs in water resources systems requires the development of tools that make it possible to predict the behavior of the aquifer under different conditions. Studies on the freshwater-saltwater interface either in steady or transient conditions has become necessary in designing and planning of groundwater systems in coastal areas. The 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.

In nature the freshwater-saltwater interface seldom remains stationary. Large scale recharging into and withdrawals from the aquifer, result the movement of the interface from the steady position to another. The main objectives of this study are to develop a numerical model to understand the behavior of the freshwater-saltwater interface and to evaluate the effects of different hydro-geological settings and to simulate different recharge events in the Walawe river basin in Sri Lanka.
Modeling 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 about freshwater saltwater interface, now widely cited as the Ghyben – Herzberg principle, is based on the hydrostatic equilibrium between fresh and saline water. After introducing Ghyben - Herzberg principle, several analytical solutions were published to describe various forms of boundary conditions of cross sectional systems. Glover [6] presented a approximated analytical solution considering the seepage flow at the seaward boundary. Van Der Veer [17] presented an analytical solution to determine the steady position of the interface, accounting the fresh groundwater flow towards the sea. Bear [1,2] provides an excellent mathematical description of the problems related to seawater intrusion in coastal aquifers.

Recently the studies involving the movement of fresh groundwater and saltwater in coastal aquifer systems are classically studied using two different approaches (Reilly and Godman) [12]. In the first approach, freshwater and saltwater are assumed completely immiscible and a sharp interface exists between these two phases. The sharp interface models which solve the coupled freshwater and saltwater flow equations have been developed with different numerical techniques (Shamir and Dagan [14]; Vappicha and Nagaraja [18]). A finite element method solution with indirect toe tracking technique was presented by Wilson and Sa Da Costa [20]. Polo and Ramis [10] discussed an unconditionally convergent finite difference approach to solve 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)[5].

In the other approach, the freshwater and saltwater are assumed to be in a dynamic equilibrium resulting from the flow and dispersion mechanisms within the aquifer. Currently several solute transport models are commercially available for the simulation of seawater intrusion. SUTRA is widely used, 2D vertical cross section model (Voss)[19]. Nusret [9] used SUTRA model to analyse and forcast the position of the interface in Erzin basin, Turky. Craig and Narayan [3] described the movement of salt to the underlying groundwater system in a saline disposal complex in north Australia, using SUTRA model. Three dimensional, density dependent solute transport codes have been developed (Huyakorn et al, [7]; HST3D).

Density dependent solute transport models has limited to two dimensional vertical cross sections. Three dimensional cases are limited in their application to regional coastal systems by computational constraints (Essaid) [5]. Sharp interface models are useful for both vertical cross sections as well as aerial simulations and can represent the bulk freshwater and saltwater flow characteristics of the system. The sharp interface approach, in conjunction with integration of the flow equations over the vertical, can be applied aerially to large physical systems (Essaid) [5].
MATHEMATICAL DEVELOPMENT OF THE SHARP INTERFACE MODEL

Sharp interface models couple the freshwater and saltwater flow based on the continuity of flux and pressure. In this approach, together with Dupuit approximation, for each flow domain the equation of continuity may be integrated over vertical direction and come up with following system of differential equations (Bear [1]).

$$\frac{\partial}{\partial x} \left[ K_f (h' - h) \frac{\partial h'}{\partial x} \right] + \frac{\partial}{\partial y} \left[ K_s (h' - h) \frac{\partial h'}{\partial y} \right] + q_f = S_i \frac{\partial h'}{\partial t} - \delta \left( \frac{1 + \delta}{\alpha \delta} \right) \left( \frac{\partial h'}{\partial t} - \frac{\partial h'}{\partial t} \right) + \alpha \theta \frac{\partial h'}{\partial t}$$

(1)

$$\frac{\partial}{\partial x} \left[ K_s (h' - z^i) \frac{\partial h'}{\partial x} \right] + \frac{\partial}{\partial y} \left[ K_s (h' - z^i) \frac{\partial h'}{\partial y} \right] + q_s = S_i \frac{\partial h'}{\partial t} + \theta \left( \frac{1 + \delta}{\alpha \delta} \right) \left( \frac{\partial h'}{\partial t} - \frac{\partial h'}{\partial t} \right)$$

(2)

The location of the interface elevation is given by

$$h' = \frac{\rho_f}{\rho_f - \rho_f} h^f - \frac{\rho_f}{\rho_f - \rho_f} h'$$

$$\Rightarrow \quad h' = (1 + \delta) h^f - \delta h'$$

(3)

where \( \rho_f \) and \( \rho_f \) are specific weight in fresh and salt water respectively, \( h' \) and \( h' \) are the piezometric heads of freshwater and saltwater regions, \( q_f \) and \( q_s \) are flow rate in fresh and salt water respectively. \( K_f \) and, \( K_s \) represent the hydraulic conductivity in fresh and salt water regions. Storage coefficients in fresh and salt water regions are given by \( S_i \) and \( S_i \) respectively. \( \theta \) is the porosity of the aquifer media. \( \alpha = 1 \) for unconfined aquifer and \( \alpha = 0 \) for confined aquifer.

Numerical Modeling

Except for very simple systems, analytical solutions of those two coupled non linear partial differential equations are rarely possible. Various numerical methods must be employed to obtain approximate solutions. One of the approaches is the finite-difference method. From equation (1) and (2), it is possible to derive a numerical model using implicit finite difference techniques. The continuous system described by above two equations are replaced by 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 entered finite difference grid which allows for variable grid spacing.

To solve the two simultaneous linear algebraic difference equations, there was a necessity of a numerical technique. The Strongly Implicit Procedure -SIP (Remson et al, [13]) was used as a suitable numerical technique. Empirical evidence suggests that for cases of flow in heterogeneous or anisotropic media, the strongly implicit procedure is much faster than the other methods. Also the strongly implicit method does not depend upon the complexity of the problem.
EFFECT OF HYDRO-GEOLOGICAL FACTORS

To investigate the effect of hydro-geologic factors mainly, specific storage, porosity and hydraulic conductivity on the dynamics of the freshwater-saltwater flow systems, a 2km × 2km horizontal strip through an unconfined aquifer has been simulated by changing the hydro-geological properties while observing the system’s transient responses. The effect of the specific storage was evaluated by increasing the storage coefficient by orders of magnitude. The change in storage coefficient does not affect the location of the interface. The system responds in almost same manner for different specific storage values because most of the water to fulfill the changes in storage is coming from the drainage of water table rather than elastic storage. The other factor which illustrates the storage of the aquifer is the porosity. To investigate the effect of porosity on the behavior of the flow system, the porosity was changed from 0.1 to 0.4 in increments of 0.1. The change in the porosity does not lead to change in the position of the interface. It leads the 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 500m away 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. Theoretically it can be explained as the freshwater heads fall to steady state more rapidly since less water must drain from the pores and the interface change more rapidly.

Another factor affecting the change of the position of freshwater-saltwater interface is hydraulic conductivity. The hydraulic conductivity was changed over the range of $10^{-3}$ m/s to $10^{-4}$ m/s. Those values are in the hydraulic conductivity range for clean sand or basalt aquifers. Figure 2 explains that the changes in hydraulic conductivity have quite an impact on the steady position of the interface. The change in hydraulic conductivity makes the changes in the transmissivity and it affects the head gradients necessary to maintain the freshwater flux. This process showed that the model is very sensitive with respect to changes in hydraulic conductivity than other hydro-geological factors.
APPLICATION TO WALAWE RIVER BASIN

Hydrogeology of Walawe River Basin
The Walawe River basin is located in the southern part of Sri Lanka, between North latitudes 6° 00’ and 6° 40’ and East longitudes 80° 40’ and 81° 10’ (Figure 3). The catchment area of the basin is 2442 km² and it is the major irrigation area in the dry topics of southern Sri Lanka. Walawe river flows from north to south with the total river length of 105km (Statkraft Groner [16]).

The Coastal Plains in the lower part of the Walawe basin, covering major part of the southern region has elevation less than 6m above Mean Sea Level (MSL), parallel to the coast. The width of the coastal plains generally ranges from 2 km to 10 km. Coastal alluvial soils as well as laterites cover the area parallel to the coast. It includes the river sediments and fine to medium green quartzite sand, silty sands of the plains and grey to dark grey beach sands. Groundwater within the area is constrained by the unconsolidated
alluvial and deltaic sediments, which were deposited by the Walawe River and its distributaries (Kulatunga [8]). The porosity of sand in this region is between 0.3 and 0.5. They are excessively drained with very high hydraulic conductivity (Engineering Consultants Ltd [4]).

**Model calibration and Parameter Estimation**

A steady state simulation with 80mm average annual recharge was used to generate the situation prior to steady state. The constant freshwater flux was estimated using the estimated groundwater recharge, as 0.0457 m/day per unit area of aquifer cross section.

For this study, the field data observation is carried out in the lower part of the Walawe river basin located in the southern coastal aquifer in Sri Lanka. The set of salinity data has been measured during the period of investigation. Salinity was measured using the salinity meter, WQC-24. It detects the salinity in terms of electrical conductivity and the temperature and reproduces the salinity value as the direct measurement of psu. Using the vertical salinity profiles of the observation wells, the depth to the freshwater-saltwater interface was estimated. Interface depth was estimated as 13.5m, 21.5m and 35m in the observation wells located at 400m, 1km and 2km distances from coastline respectively. The model was calibrated by adjusting hydraulic conductivity values to match the steady state interface location with the field observed value at observation wells.

**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 the only source of recharge is from precipitation and all discharge is to the ocean. Because the lower part of the Walawe basin is not under any major stress such as extensive pumping, it was assumed that the aquifer is in the steady condition (Silva [15]).

![Figure 4. Movement of interface with groundwater recharge (R)](image-url)
From an assessment of recharge mechanisms, estimated annual groundwater recharge of 1997 to 2000 found to be varied between 50 mm/year and 100 mm/year (Ranjan et al) [11]. As realistic values to represent the groundwater recharge in Walawe basin, the simulation runs were conducted with recharge values of 50, 70, 90 and 100 mm/year. The outputs from steady state results were used as an initial condition to simulate realistic short-time effects of changes in groundwater recharge on the system. A series of interface profiles for various recharge rates were obtained using calibrated model. Location of freshwater-saltwater interface profiles for annual recharge rates in Walawe river basin are shown in Figure 4.

It shows that higher recharge can reduce saltwater intrusion effectively. The saltwater will intrude farther inland than now occurring unless the amount of additional recharge can push the seawater equilibrium surface seaward. This kind of simulations shows that any groundwater development activity in the region needs to be carefully planned with remedial measures in order to prevent the further intrusion of seawater.

CONCLUSIONS

The application of sharp model is very useful in those cases where a two-dimensional vertical cross-section adequately represents the groundwater system. 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. The model was calibrated by adjusting the hydraulic conductivity to match the observed data in the coastal aquifer in lower part of the Walawe river basin, Sri Lanka and the comparison has been found to be in reasonable agreement. The results of this study highlight the effects of recharge on saltwater intrusion and high recharge rate in the aquifer can reduce seawater intrusion effectively. If reasonably good data are available, such numerical models can be employed to provide an important means for guiding management decision.

ACKNOWLEDGEMENT

The authors would like to acknowledge the Grant-in-Aid for Scientific Research by Prof. Nobuo Mimura and Prof. Masaki Sawamoto.

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