

Seawater intrusion into coastal aquifers – a case study

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Abstract

Seawater intrusion into coastal aquifers is a major problem in almost all parts of the world. The increasing demand for fresh water in coastal regions is being met by the coastal aquifers. The development and management of fresh groundwater resources in coastal aquifers are seriously constrained by the presence of seawater intrusion. For proper management of coastal aquifers, it is necessary to assess the extent of saltwater intrusion in the aquifers. In the present study a numerical model based on solute transport, which can simulate seawater intrusion, is studied and is applied to an actual field situation. The extent and pattern of seawater intrusion in the region is simulated under the present situation. Simulations are also carried out to find the effect of pumping rate on the intrusion pattern in the vertical direction. The model is applied to an actual field problem. The model is calibrated in steady state to estimate model parameters such as conductivity and specific yield. Simulation runs are performed for the model to calculate groundwater heads in the region for a period of 180 days. When these heads are compared with the observed heads it yields a correlation coefficient of 0.75. The model is then calibrated in the transient state and when the transient heads are compared with observed heads a correlation coefficient of 0.98 is obtained. The model is then applied to simulate seawater intrusion in the horizontal direction. It is seen that the advancement of the seawater intrusion front is at maximum for a depth of 28–40m from the ground surface. The simulation is also carried out to see the effect of the pumping rate on the advancement of the seawater intrusion front in the vertical direction in the region along the three pumping wells namely Karichal, Pollinkudi and Adimalathura. The rate of advancement in the intrusion front in the Pollinkodi pump well is found to be greater than the other pumping wells.

Keywords: seawater intrusion, coastal aquifers, seawater intrusion front, extent and pattern of seawater intrusion, variation with pumping rate.



1 Introduction

In coastal areas coastal aquifers prove to be an important source of groundwater resource. Under-utilization of the available water resources means that the valuable fresh water will discharge naturally into the sea and be wasted. Over exploitation of the groundwater resources causes degradation of water quality due to the encroachment of seawater. Hence the development and management of coastal groundwater aquifers is an important issue. When groundwater is pumped from the aquifer, the fresh water level is lowered and the sea intrudes into the aquifer. With excessive pumping, the natural hydraulic gradient towards the sea may be reversed and the intrusion may extend to the pumping borehole, making it saline. For proper management of coastal aquifers, it is necessary to assess the extent of saltwater intrusion in the aquifers.

2 Objectives

The present study aims at simulating seawater intrusion into coastal aquifers using already developed numerical code available from literature and to apply the same to a case study. Hence the following objectives are formulated:

- 1) To apply a numerical model based on the theory of groundwater flow and solute transport to simulate seawater intrusion.
- 2) To identify an actual field problem and collect field data pertaining to the problem that would serve as input information to the numerical model.
- 3) To idealize the problem so that the solute transport numerical model is conveniently fitted to the field situation.
- 4) To calibrate the model using the known groundwater heads and estimate the parameters like conductivity and specific yield.
- 5) To estimate the extent and pattern of seawater intrusion in the study region.

3 Theoretical basis

This section describes the flow equation and solute transport equation given by Langevin *et al.* [6] wherein both equations form the governing equation for the simulation of seawater intrusion.

3.1 Mathematical model

The form of the flow equation used in the model is as follows:

$$\nabla \left[\rho K_f \left(\nabla h_f + \frac{\rho - \rho_f}{\rho_f} \nabla z \right) \right] = \rho S_{sf} \frac{\partial h_f}{\partial t} + n \frac{\partial \rho}{\partial C} \frac{\partial C}{\partial t} - \rho_s q'_s \quad (1)$$

where K_f is the fresh water hydraulic conductivity tensor given by $K_f = k \rho_f g / \mu_f$ [LT^{-1}], n is porosity [-], ρ is fluid density [ML^{-3}], t is time [T], q is specific



discharge [LT^{-1}], and q'_s is a source or sink [T^{-1}] of fluid with density ρ_s . k is the permeability tensor [L^2], μ is dynamic viscosity [$ML^{-1}T^{-1}$] and h_f is fresh water head given by

$$h_f = \frac{p}{\rho_f g} + z \quad (2)$$

p is pressure [$ML^{-1}T^{-2}$], g is gravity [LT^{-2}], and z is the upward coordinate direction.

S_{sf} is the fresh water specific storage [L^{-1}] defined as the volume of water released from storage per unit volume per unit decline of fresh water head, and C is the concentration of solute mass per unit volume of fluid [ML^{-3}].

The general form of the solute transport equation is given as:

$$\frac{\partial(nC)}{\partial t} = \nabla \cdot (nD \cdot \nabla C) - \nabla \cdot (qC) - q'_s C_s \quad (3)$$

where D is the hydrodynamic dispersion coefficient tensor [L^2T^{-1}] and C_s is the source or sink concentration [ML^{-3}].

4 Methodology

The flow and solute transport equations are numerically solved using software SEAWAT. The entire period of simulation is divided into different stress periods depending on the strength of source or sink (q'_s). Each stress period is further divided into one or more time steps to produce results more accurately. The length of time step is then calculated during the simulation by SEAWAT to satisfy the stability constraint given in (4)

$$\Delta t = \frac{n}{q'_s} \quad (4)$$

Then the flow equation and solute transport equation are solved using the explicit method. With the explicit method, a lagged approach is used for assigning fluid densities in the flow equation. This means that fluid densities are calculated with solute concentrations from the previous time step. Advective flux from the flow solution for the current time step is then used to solve the transport equation in the current time step. This solute concentration is then used to update the fluid density. This updated fluid density is then used to solve flow equation for the next time step. This procedure is repeated until all the stress periods in the entire simulation are complete.

5 Study area

The study region lies in the Thiruvananthapuram district of Kerala. The coastal region stretches for about 78km and has an elevation less than 8m above mean sea level (MSL) parallel to the coast. Coastal alluvial soils as well as laterites cover the area parallel to the coast. The average rainfall is around 150cms per annum. The study region is a portion of the coastal region of



6 Idealization of the field problem

6.1 Spatial discretisation

To simulate the groundwater interaction in the region a finite-difference model grid was constructed. The grid consists of 40 columns and 40 rows. The area was conceptualized as a five layer system. The five layer system was decided based on the information obtained from a bore log of a near by site and the presence of the river as a boundary. The bore log revealed that the stratum beneath the study area consisted of four layers with respect to the variation in the stratum. The river boundary was considered as a separate layer and thus the area was conceptualized as a five layer system. Layer 1 and Layer 2 as Upper Aquiclude while Layer 3 as Unconfined aquifer and Layer 4 as Lower Aquiclude. The Confined aquifer is represented as Layer 5. This gives an idea of horizontal advancement of salinity intrusion in each layer.

To get a precise picture of vertical advancement of intrusion, unit width in Y-direction is assumed and the domain is thus reduced to a two dimensional domain. To simulate the seawater intrusion along vertical sections, a finite-difference model grid was constructed with 1 row (representing unit width), 40 columns and 5 layers.

6.2 Boundary conditions

To simulate the groundwater heads and seawater intrusion, no-flow boundary cells were assigned to the rock formation on the North West of the study region, which is represented by the green cells in Fig.2. River boundary conditions were applied to the two canals in the study area shown by dark blue lines in Fig2. Constant head and constant concentration cells represent the sea (region in light blue in Fig.2) with head value set to 0 and constant salt concentration set to 35000 mg/lit. Recharge from rainfall infiltration is calculated using the rainfall infiltration factor and was assigned to Layer 1. The strength of source or sink (q'_s) in (1) is the term that represents the recharge value. Recharge from rainfall is given by

$$R = f \times A \times \text{Normal rainfall in monsoon season} \quad (5)$$

where R = Recharge from rainfall

f = rainfall infiltration

A = area of computation for recharge.

The rainfall infiltration factor for laterite soil recommended by the groundwater resource estimation committee is 0.07. Since the recharge changes over period of time the entire period of simulation was divided into 18 stress periods so that recharge is constant for a given stress period.

To simulate the seawater intrusion along the vertical direction, seawater hydrostatic conditions were applied to the left boundary (boundary near to sea) with a constant concentration of 35000 mg/lit. Constant freshwater heads were assigned to the cells along the sea boundary using a head value of 0 m. Constant



concentration of 0 mg/lit was assigned along the land boundary. Five vertical sections were considered so that each vertical section is across one pumping well out of the five wells chosen.

6.3 Modeling approach

Seven observation wells located near to the pumping wells were selected in the study region and water level data was collected for a period of 180 days from April to September. The pumping wells are shown in red dots and observation wells are shown in green dots in Fig.2. The model was calibrated in steady state condition by using water level data from these observation wells. A number of trial runs were made by varying the hydraulic conductivity values of the layers until the differences between the computed and observed values were minimum. The results thus obtained from steady state simulation were used as initial condition and the model was calibrated in transient condition. The calibrated model under transient condition was then used to predict the water levels in the observation wells for a period of one year.

The seawater intrusion in the horizontal direction (X-direction) was simulated for the three dimensional domain using the hydraulic conductivity and storage values obtained from transient state. Calibration was achieved by adjusting the dispersion coefficient for the model within a reasonable range until the values indicating the position of the saltwater interface matched with those values observed in the field. To simulate the seawater intrusion along vertical sections, sections were taken along the three pumping wells – Karichal, Pollinkudi, and Adimalathura.

7 Results and discussions

7.1 Simulation of groundwater head

The model was calibrated in steady state to estimate model parameters like conductivity and specific yield. Simulation runs were performed in steady state for the model to calculate groundwater heads in the region for a period of 180 days. The steady state head values for different wells were obtained and when these heads were compared with the observed heads it yielded a correlation coefficient of 0.75. The model was also calibrated and run in transient state to yield model parameters and transient heads.

Hydraulic Conductivity

Upper aquiclude	-	0.004 m/day
Unconfined aquifer	-	25 m/day
Lower aquiclude	-	0.002 m/day
Confined aquiclude	-	8.5 m/day

Specific Yield

Aquiclude	-	1×10^{-5}
Unconfined aquifer	-	0.005
Confined aquifer	-	0.0006



Effective Porosity	-	0.15
Total Porosity	-	0.3
Dispersivity (m)		
α_L	-	10
α_T	-	0.1
Dispersion Coefficient (m²/day)	-	0.35

7.2 Simulation of seawater intrusion

The seawater intrusion front in the region in the horizontal direction for the five layers is simulated. For the first three layers intrusion is not seen up to 1400m (in X direction) from the origin of model domain. This can be attributed to the fact that no-flow boundary condition is applied in these layers. From 1400m the intrusion is seen in the three layers. For the first two layers, seawater intrusion front is 250m from the coast and for the third layer the intrusion front is 500m from the coast. For the fourth and fifth layer we have not applied no-flow boundary condition since it is assumed that the depth of rock does not extend to the depth where these layers are present. Hence unlike the first three layers wherein there was no intrusion due to the presence of rock up to 1400m, it is seen that there is advancement of the seawater intrusion front in these layers even within this distance of 1400m. For these two layers up to a distance of 1400m from the origin of the model domain the intrusion front is 200m and after 1400m the intrusion front is 400m from the coast. A sample result obtained for layer 1 and layer 5 are shown in Figures 3 and 4.

The seawater intrusion front in the vertical direction along the three pumping wells Karichal, Pollinkodi and Adimalathura is simulated.

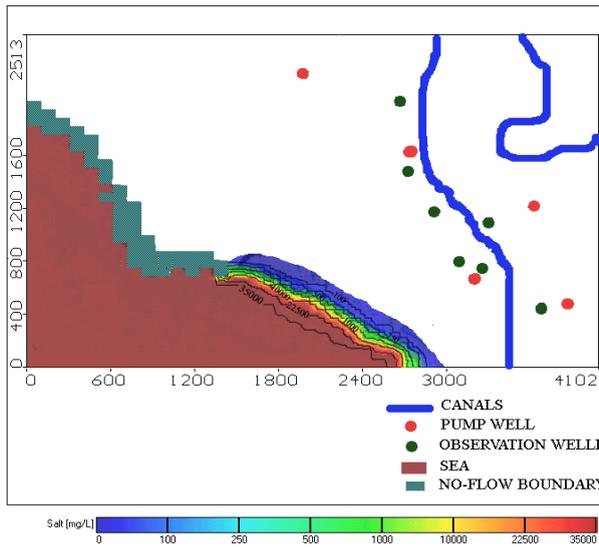


Figure 3: Extent of seawater intrusion in the horizontal direction for layer 1.

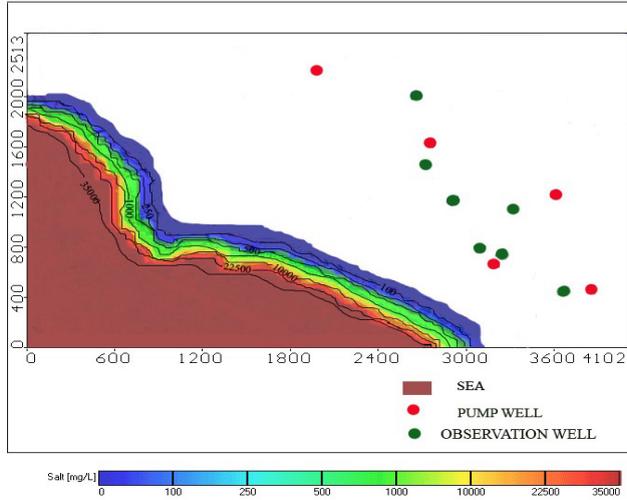


Figure 4: Extent of seawater intrusion in the horizontal direction for layer 4 and layer 5.

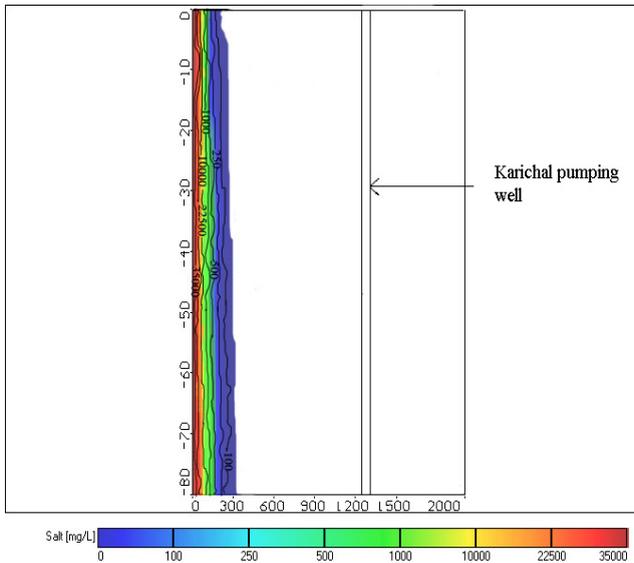


Figure 5: Extent of seawater intrusion for a vertical section along the Karichal pump well.

For the section along the Karichal pumping well the toe of saltwater intrusion front lies 240m from the coastal line. For the section along the Pollinkodi pumping well the toe of saltwater intrusion front lies 450m from the coastal line. In this well the effect of seawater intrusion is seen in a depth range of 20–60m

below ground surface. For the section along the Adimalathura pumping well the toe of saltwater intrusion front lies 240m from the coastal line. The extent of seawater intrusion along the Karichal pump well and Pollinkodi pumping well are shown in Fig. 5 and Fig.6 respectively.

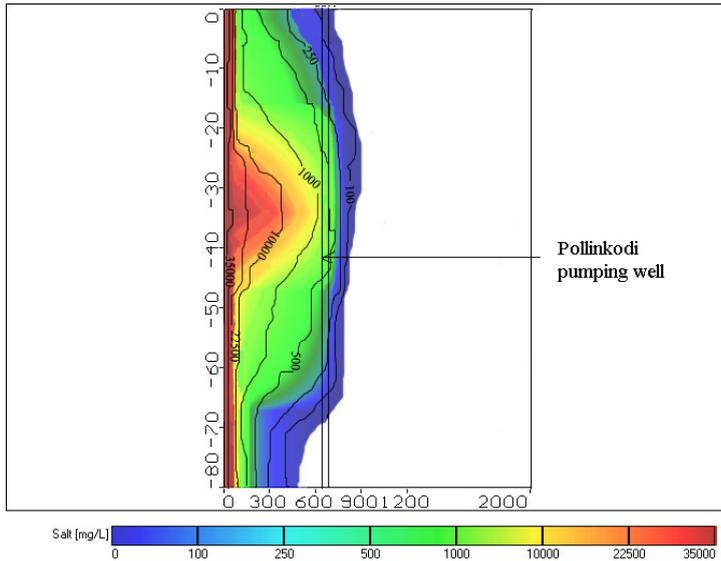


Figure 6: Extent of seawater intrusion for a vertical section along the Pollinkodi pump well.

8 Conclusion

The model was calibrated in steady state to estimate model parameters like conductivity and specific yield. Simulation runs were performed for the model to calculate groundwater heads in the region for a period of 180 days. The model was then applied to simulate seawater intrusion in horizontal direction. From the simulation it is seen that for a depth of 40m from ground surface intrusion is not seen up to 1400m (in X direction) from the origin of the model domain. This can be attributed to the fact that no-flow boundary condition is applied in these layers. From 40m to 80m, there is advancement of the seawater intrusion front even within this distance of 1400m. This may be due to the fact that the depth of rock does not extend to the depth where these layers are present and hence no-flow boundary condition is not applied to these two layers. As a result, in this depth range (40–80m) up to a distance of 1400m measured from the origin of the model domain, the intrusion front has advanced to a distance of 200m from the coast.

From the simulation it is seen that from a distance of 1400m measured from the origin of model domain, seawater intrusion front is observed in all the five layers. From ground surface up to a depth of 28m the intrusion front has

advanced to a distance of 250m from the coast. From 28–40m depth, the intrusion front seems to have advanced to a distance of 500m from the coast. From 40–80m depth, the presence of the intrusion front is seen up to a distance of 400m in the horizontal direction. Thus the advancement of seawater intrusion front is at maximum for a depth of 28–40m from the ground surface. The extent of seawater intrusion is less up to a depth of 28m and this may be due to the recharge from the canals present in the region.

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