

into aquifer systems as a result of different factors. However, modeling saltwater intrusion is considered difficult. Factors such as heterogeneity of the aquifer hydraulic properties, the complicated aquifer geometries and the temporal and spatial variability in groundwater density make it difficult to model seawater intrusion (Morgan et al., 2013).

The accuracies of model outputs are strongly based on the assumptions made on the model input parameters. Seawater intrusion model results for the saltwater–freshwater interface position, for example, are strongly affected by different factors such as boundary conditions, initial (head and concentration) conditions and aquifer hydraulic properties. Furthermore, nowadays, submarine groundwater discharge (SGD) is also becoming an important issue to be considered in modeling coastal groundwater systems. Owing to seawater intrusion, the land driven fresh groundwater can discharge to the seafloor through the leaky confining unit and the process is called SGD (Post et al., 2013; Moore, 2009; Church, 1996). This kind of discharge decreases with the increase in distance offshore and is zero where the tip of the interface touches the leaky confining unit (Beebe et al., 2011).

Several authors have studied seawater intrusion and the position of the saltwater–freshwater interface owing to different factors in coastal aquifers. Strack (1976) developed an analytic solution for the regional interface problems in coastal aquifers based on the single-valued potentials, the Dupuit assumption and the Ghyben–Herzberg formula for the steady state flow conditions. The Strack (1976) analytic solution has been widely used by different researchers to explore seawater intrusion in coastal aquifers (e.g., Morgan et al., 2013; Beebe et al., 2011; Aharmouch and Larabi, 2001; Wriedt and Bouraoui, 2009; Mazi, 2014; Naderi et al., 2013). Different seawater intrusion assessment methods have also been developed based on the Strack (1976) analytic solution (e.g., Werner et al., 2012; Pool and Correra, 2011).

Other authors like Huyakorn et al. (1996), who presented a numerical model based on the sharp interface approach and taking into account the flow dynamics of saltwater and freshwater, Motz (1992), who proposed an analytic solution for calculating the

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critical pumping flow rate in an artesian aquifer, and Bower et al. (1999), who modified the critical interface rise based on the analytic solution which allows the critical pumping rate to be increased are also some of the well-known studies conducted on seawater intrusion in coastal aquifers.

However, none of the above papers consider the influence of SGD on the seawater–freshwater interface position. There is no possibility to simulate the offshore groundwater discharges using the above analytic solutions, unless modifications are made to include the offshore outflow zone of the land driven fresh groundwater through the seafloor by taking model extent offshore into consideration.

Recently, Bakker (2006) has modified the Strack solution so as to include the offshore freshwater outflow zone. It is a solution for a steady interface flow in confined coastal aquifers discharging to a semi-confined section below the ocean. Bakker has shown that the tip of the saltwater–freshwater interface can perhaps touch the leaky confining unit at some distance offshore, and this depends on the head of the land driven fresh groundwater and the leakage factor of the seafloor. Hence, the decision on how long a model should be extended offshore for accurate simulations of the interface position is also an important consideration when modeling coastal groundwater flow systems.

The objective of this manuscript is therefore to investigate the influence of SGD on the position of saltwater–freshwater interface. To do so, comparing the steady state interface location when two conceptualizations are used in both analytic and numerical modeling techniques could be very important. The first conceptualization is based on the Strack (1976) analytic solution, assuming that the tip of the interface lies at the shoreline; while, the second conceptualization is based on the Bakker (2006), taking the distance offshore into consideration.

1.1 Common parameters and values used

A homogeneous and isotropic coastal aquifer with confined and semi-confined sections and of constant thickness H [L] was considered in this generic research. A Steady state condition is assumed and pumping is not considered. The inflow to the aquifer at the

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interface all along 0 to d , and $Z_2 + 30$ will give the interface hydraulic heads all along 0 through $-L$. Remember that, the values for Z_1 and Z_2 are based on X_1 and X_2 (from Eqs. 13 and 15), respectively. Therefore, Z_1 and Z_2 will represent a list of 100 numbers each. This implies that we have 100 points onshore and 100 points offshore to plot.

2.2 Numerical modeling

In addition to their use as planning tools for improving water supply and management, numerical models of groundwater systems are also useful for understanding groundwater flow processes. In terms of the use of modeling packages, groundwater flow systems can be divided into two, i.e., groundwater flow processes with constant density and the one with variable density. Simulating the groundwater systems in coastal aquifers which include saltwater and freshwater requires the use of a numerical modeling code that solves the variable-density flow equation (examples and perhaps widely used packages are SEAWAT and SUTRA).

SEAWAT is a generic MODFLOW/MT3DMS based computer program designed to simulate three-dimensional variable-density groundwater flow coupled with multi-species solute and heat transport. While, SUTRA is a general-purpose, density-dependent, fluid flow and mass-transport numerical model that applies a finite element and integrated finite-difference hybrid method, which is mainly used to model both the coastal surficial and confined aquifers (Werner et al., 2013). In this case, the model used to investigate the impact of SGD on the position of saltwater–freshwater interface is the three dimensional SEAWAT model. SEAWAT has been used widely for groundwater studies including saltwater intrusion in coastal aquifers.

The type of aquifer considered in this paper is a confined coastal aquifer which is hydrogeologically connected with the seawater. Similar to what was done in the analytic modeling section, numerical modeling was conducted based on the Strack (1976) and Bakker (2006) analytic solutions for the interface problems. The other consideration, in this simulation was that the confining unit offshore (the sea floor) is assumed to

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be a leaky confining unit. The common parameters used in both simulation cases are listed in Table 1.

2.2.1 Case-1: modeling with no distance offshore

To obtain a steady state solution, the simulation run was divided into 10 stress periods, which in turn are divided into 10 000 time steps and 70 000 days of period length each, which corresponds to a total simulation period of 700 000 days. Modeling was conducted for case-1 by constructing a three dimensional SEAWAT model with an inland distance of 2600 m, based on the Strack (1976) analytic solution.

The SEAWAT model was used to simulate variable density groundwater flow in a three-dimensional cross section with 1 row, 130 columns, and 20 layers. The size of each model cell was set to 20 m horizontal by 1 m vertical. The top and bottom sides of the model were set to no-flow boundaries. The left side boundary is occupied by the seawater column with a constant head of 30 m and constant density of 35 kg m^{-3} ; while, the right side boundary was set to a constant flux freshwater with an inflow rate of 1 m^3 and density of 0 kg m^{-3} .

The model was initially run for 50 000 days in a steady state simulation flow type. Then, the initial and prescribed head was taken from the steady state simulation as an input for the transient simulation flow type. Therefore, the initial and prescribed head used in this simulation was 30 m. The initial concentrations were based on seawater concentrations, 35 kg m^{-3} for columns 2 to 129 in all layers; while, column 1 (seawater column) was fixed to a concentration of 35 kg m^{-3} . The concentration for column 130 (freshwater column) was also set to 0. A uniform and isotropic value for hydraulic conductivity was set to 260 m day^{-1} , the porosity was set to 0.35, and the values for longitudinal and transverse dispersivities were set to 0.1 m each. The specific storage was also set to 0.0001.

The SIP package of MODFLOW and the GCG package with the finite-difference option of MT3DMS/SEAWAT were used to solve systems of the flow and transport equations, respectively. The SIP solver was used with a head convergence criterion

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3.2.2 Case-2

This conceptualization was based on the Bakker (2006) analytic solution for the interface problems. Similar to case-1 above, the concentration contour line at the 50 % of the maximum concentration was chosen to represent the interface location. Accordingly, the tip of the seawater–freshwater interface was found at an offshore distance of 300 m; while, the toe was found at an inland distance of 700 m (Figs. 7 and 8). Similar to case-1, the distance to the toe location found in this case is shorter than the distance found in case-2 of the analytic solution section.

3.3 Comparison between case-1 and case-2 results of the numerical modeling

Similar to the analytic solution, the numerically simulated results for case-1 and case-2 are also different. Furthermore, the locations and shapes of the interfaces in these two cases are different. The main reason for this situation is, therefore, the SGD incorporated in case-2. Therefore, ignoring the influence of SGD on the interface position when modeling coastal groundwater systems, especially those with confined and semi-confined sections, overestimates the interface location.

3.4 Comparison between analytic and numerical modeling results

Analytic solutions for the position of the saltwater–freshwater interface are based on the sharp interface approximations. The advantages of analytic solutions are that they are considerably less computationally intensive and require less data (Werner et al., 2012). However, sharp interface approximations can only be used in areas where the mixing zone can be ignored; while, in reality, mixing between freshwater and saltwater occurs in all coastal aquifers as a result of dispersion, changes in head, changes in hydraulic conductivity and tides (Shalev et al., 2009). In fact, the extent of mixing varies from a few tens of centimeters in tight clays or sandstone to several tens of meters in karstic limestone (Dausman and Langevin, 2005). But mixing is always there, regardless of

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its extents. Therefore, analytic solutions obviously overestimate the extent of saltwater penetration further inland.

In reality, freshwater overlies the mixing zone which in turn overlies saline water. It is not, therefore, possible to provide stable and accurate results using analytical solutions, unless a correction factor is incorporated to include the influence of mixing. However, the complex density-dependent groundwater flow and solute transport models provide stable and convincing results when employed with proper spatial and temporal discretizations.

In this case, simulation results for the interface heads from the two analytic solutions were corrected by the empirically derived dispersion factor $[1 - (\alpha_T/b)^{1/6}]$ developed by Pool and Carrera (2011) to include the influence of mixing on the interface location, where α_T is transverse dispersivity and b is aquifer thickness. While, simulation results for the saltwater–freshwater interface position from the density-dependent solute transport numerical model (SEAWAT), which includes advection and dispersion, are believed to be accurate.

The transverse dispersivity used in both of the two cases of the numerical modeling section was 0.1. Therefore, the correction factor (f) can be calculated as follows:

$$f = \left[1 - \left(\frac{\alpha_T}{b} \right)^{1/6} \right]$$

$$f = \left[1 - \left(\frac{0.1}{20} \right)^{1/6} \right] = 0.5865$$

As shown in Figs. 9 and 10, the analytic solution results for both case-1 and case-2 were corrected by the correction factor (f). Finally, the corrected analytic solutions became very close to the numerically simulated values. Initially, the location of the toe for case-1 was found at an inland distance of 1300 m; while, it was found at a distance of 880 m from the numerical modeling. However, after correcting the analytic solution

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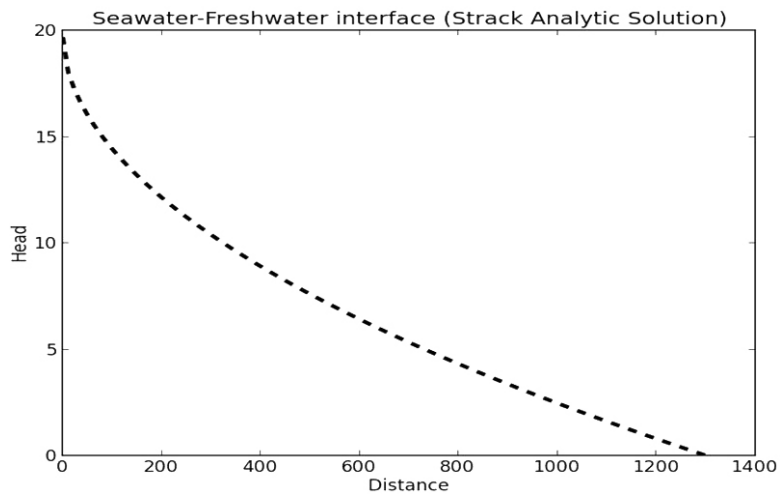


Figure 2. Strack (1976) seawater–freshwater interface.

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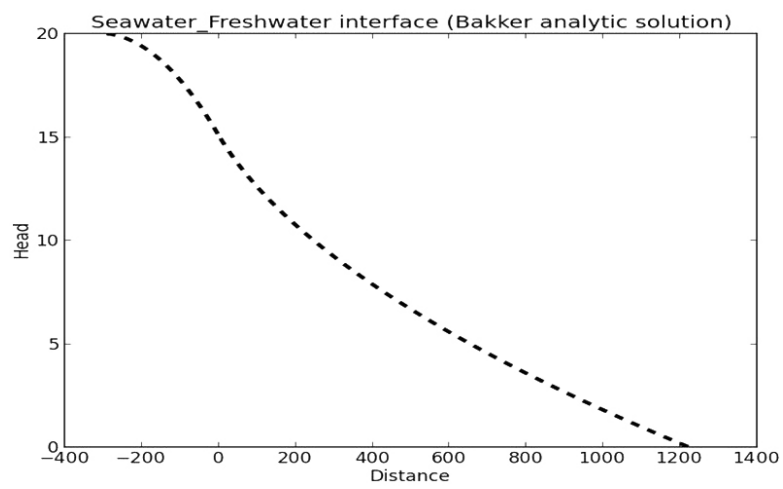


Figure 3. Bakker (2006) seawater–freshwater interface.

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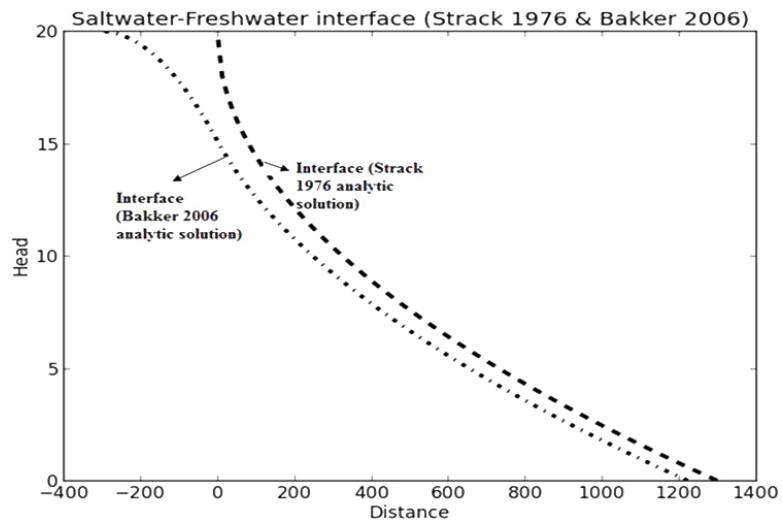


Figure 4. Plotting the two interface solutions in one.

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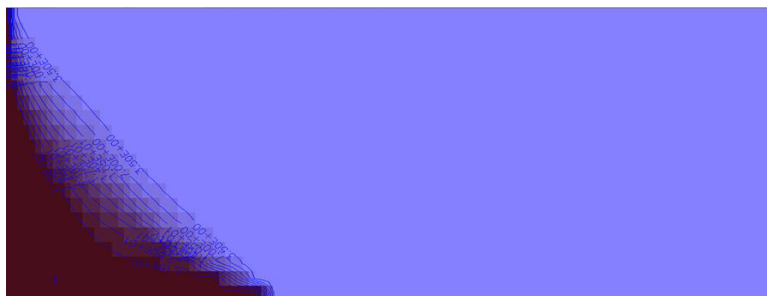


Figure 5. Contour map of case-1.

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Figure 6. Seawater–freshwater interface (at 50 % of the maximum concentration) of case-1.

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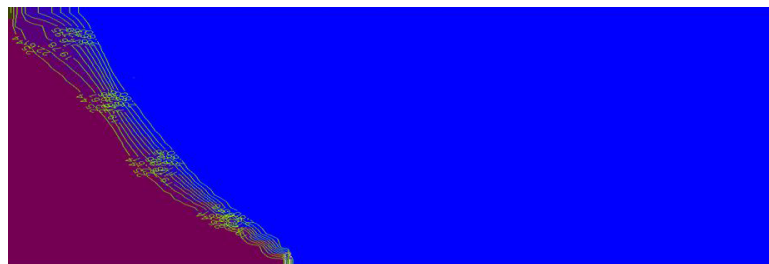


Figure 7. Contour map of case-2.

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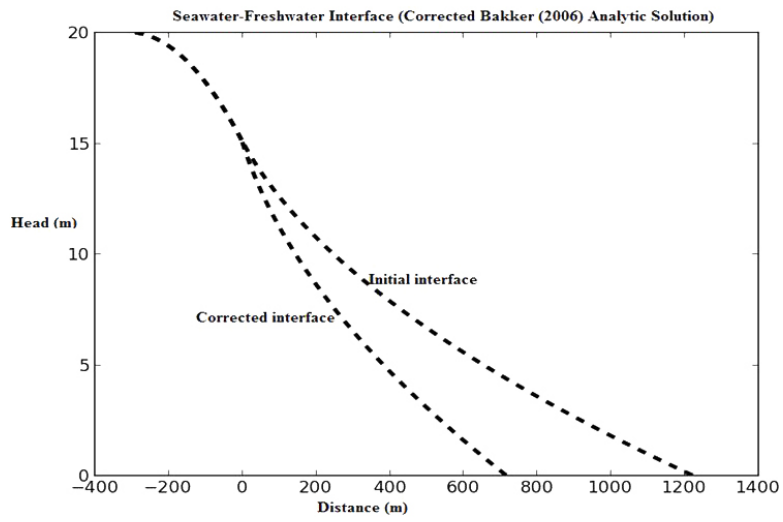


Figure 10. Corrected Bakker (2006) Seawater–Freshwater interface.