Simulation of seawater intrusion with standard groundwater codes

Frans Schaars[1], Mark Bakker[2]
[1] Artesia BV, Schoonhoven, Netherlands
[2] Water Resources Section, Faculty of Civil Engineering and Geosciences,, Delft University of Technology, Delft, Netherlands

ABSTRACT

We developed a method to simulate steady interface flow in multi-layer coastal aquifers with regular groundwater codes such as standard MODFLOW. The main step is a simple transformation of the hydraulic conductivities and thicknesses of the aquifers. Standard groundwater codes may be applied to compute the head distribution in the aquifer using the transformed parameters. For example, for flow in a single unconfined aquifer, the hydraulic conductivity needs to be multiplied with 41 and the base of the aquifer needs to be set to mean sea level (for a relative seawater density of 1.025). Once the head distribution is obtained, the Ghijben-Herzberg relationship is applied to compute the depth of the interface. The method may be applied to quite general settings, including spatially variable aquifer properties. Any standard groundwater code may be used, as long as it can simulate unconfined flow where the transmissivity is a linear function of the head. The proposed method is benchmarked successfully against a number of analytic and numerical solutions. The method is based on the analogy of interface flow and unconfined flow. We will show the consequences of using different methods for calculating the intercell conductance, and different approaches for drying and wetting cells, including the methods used in MODFLOW-NWT.

INTRODUCTION

Seawater intrusion in coastal aquifers may be simulated with computer codes that combine groundwater flow, contaminant transport, and density effects, such as SEAWAT (Langevin et al. 2008), SUTRA (Voss and Provost 2010), and FEFLOW (Diersch and Kolditz 2002). Alternatively, seawater intrusion may be simulated with the SWI package for MODFLOW (Bakker and Schaars 2005) SWI does not require a vertical discretization of an aquifer, as it applies the Dupuit approximation for flow within an aquifer. As a result, SWI simulations require much less computational effort, typically at least three orders of magnitude less than the codes that solve the combined flow and transport equations (Bakker et al. 2003; Dausman et al. 2010).

Final steady-state conditions are of interest in large regional models that include a coastal boundary in order to estimate pre-development conditions in an aquifer, to design well fields in coastal aquifers, or to evaluate proposed designs to limit seawater intrusion. For such simulations, it is often sufficient to simulate flow in an aquifer as interface flow (e.g., Cheng et al. 2000; Mantoglou 2003). SWI is better suited to compute the steady position of the interface, but it is inconvenient as it requires specification of the initial interface position as well as some algorithm-specific parameters. In addition, it may take a significant simulation time before steady state is reached.

The steady position of an interface between fresh and salt water may be computed from the head with the well-known Ghyben-Herzberg equation (e.g., Bear 1972; Strack 1989; Fitts 2002). Application of the potential introduced by Strack (1976) is a common approach for the simulation of steady interface flow in a single aquifer. The Strack potential is implemented in the analytic element codes Gflow (www.haitjema.com) and AnAqSym (www.fittsgeosolutions.com). Strack's potential is applicable to aquifers with piecewise homogeneous properties. Although it is in theory applicable to multi-aquifer systems, it is inconvenient as it leads to a system of linked, non-linear differential equations (Sikkema and Van Dam 1982; Bakker 2006).

For simulation of steady interface flow in multi-aquifer systems with variable properties, it seems necessary to apply a numerical solution technique.
The objective of this paper is to present an approach to simulate the steady-state position of the interface in a heterogeneous multi-aquifer system with a standard single-density groundwater code. At steady-state, the saltwater is stagnant and the saltwater head is constant everywhere in the saltwater zone. No sinks or sources may be present in the saltwater. The simplest case of unconfined interface flow is discussed here, for more complicated examples, including multi aquifer flow we refer to Bakker & Schaars (2013) The example is solved using MODFLOW (Harbaugh et al.2000; Harbaugh 2005).

STEADY UNCONFINED INTERFACE FLOW

Consider steady unconfined interface flow in a deep aquifer so that the interface doesn't touch the bottom of the aquifer anywhere, as illustrated in Fig. 1a. The saltwater is at rest. The Dupuit approximation is adopted so that the depth D of the steady interface below sea level may be computed with the standard Ghyben-Herzberg equation as (e.g., Bear 1972; Strack 1989; Fitts 2002)

$$D = \alpha(h - z_s) \quad (1)$$

where h is the freshwater head defined as (e.g. Post et al., 2007)

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

where p is the pressure in the water. The factor α is defined as

$$\alpha = \frac{\rho_f}{\rho_s - \rho_f} \quad (3)$$

As the saltwater is stagnant, the pressure is hydrostatic and the freshwater head increases with depth as:

$$h(z) = z_s + (z_s - z)/\alpha \quad (4)$$

The thickness of the freshwater zone may be computed as

$$H = D + (h - z_s) = (\alpha + 1)(h - z_s) \quad (5)$$

So that the transmissivity becomes

$$T = (\alpha + 1)k(h - z_s) \quad (6)$$

where k is the hydraulic conductivity.

This linear relationship between head and transmissivity may be simulated with a single-density groundwater code that is able to simulate unconfined flow where the transmissivity is a linear function of the head, provided the hydraulic conductivity and bottom of the aquifer are transformed as

$$\tilde{k} = (\alpha + 1)k \qquad\qquad (7)$$
$$\tilde{z}_b = z_s$$

In Figure 1 the example is displayed for the problem of a circular island with a radius of 1000 m, a hydraulic conductivity of 10 m/d and areal infiltration of 0.001 m/d. The head is equal to h_0 along the coast. The sealevel z_s equals zero and $\alpha = 40$.

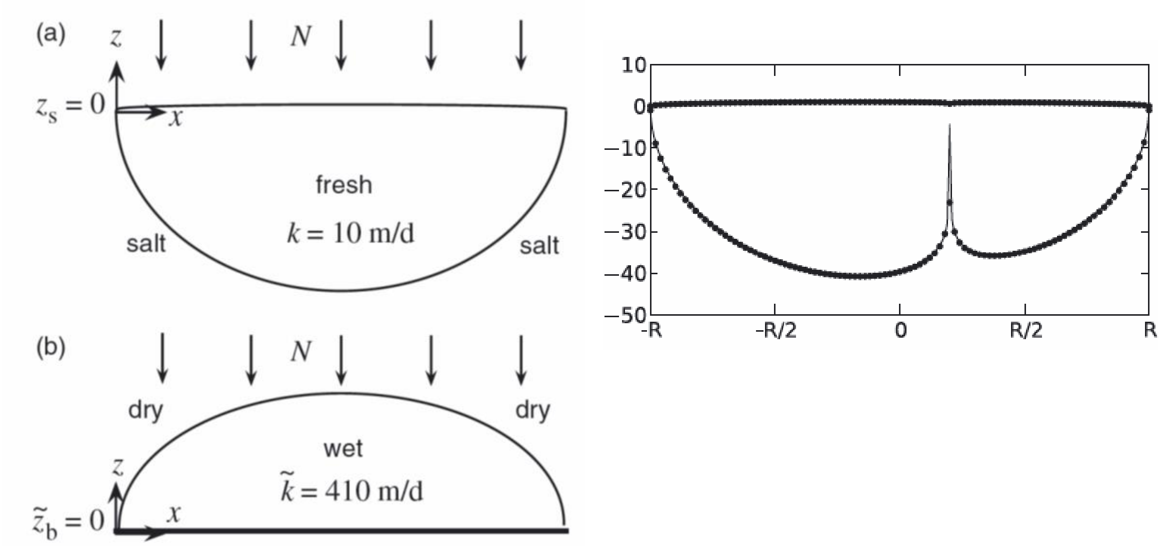

Figure 1. (a) Cross section of unconfined interface flow on a circular island, (b) equivalent unconfined flow problem in transformed model domain (vertical exaggeration much larger in bottom figure than in top figure). On the right: comparison of Strack solution (line) with MODFLOW (dots) for the simulation with a pumping well (200 m form center island, radius 0.3 m and discharge 200m^3/d).

DISCUSSION AND CONCLUSIONS

An approach was presented to simulate steady Dupuit interface flow in heterogeneous multi-aquifer systems with standard single-density groundwater codes. Such cases cannot be solved with codes that implement the more elegant Strack potential, which is applicable to piecewise homogeneous aquifers only. Accuracy of the approach was demonstrated through comparison with exact interface flow solutions for homogeneous aquifers obtained with Strack's potential. The basic idea of the approach presented in this paper is to transform the domain such that it is identical to an unconfined flow problem.

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Contact Information: Frans Schaars, Artesia BV, korte weistraat 12, 2871BP Schoonhoven, the Netherlands, Email: f.schaars@artesia-water.nl