Numerical Simulation of a Coastal Aquifer in Rhodes Island

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ABSTRACT
Numerical models are developed and applied to a heterogeneous unconfined coastal aquifer located at the northern part of Rhodes Island in Greece. An initial single phase flow model is used to determine the aquifer hydraulic conductivities using PEST algorithm. Then a more complex three-dimensional variable density mass transport model is developed based on finite elements and FEFLOW. The estimated piezometric head distribution is identical for both single flow and mass transport model, except in a narrow region near the coast.

INTRODUCTION
Rhodes is a very touristy island of the South-Eastern Aegean Sea. The available water resources are limited, while water demands are very high, especially during summer months. Therefore, reliable aquifer models are needed in order to manage island water recourses and to determine their vulnerability on future water balance changes. The primary goal of this study is to develop such model for the most important aquifer of the island. Since no field data concerning the aquifer parameters are available, an initial calibration is performed. Parameter estimation using variable density models is a complex and data demanding procedure. Therefore, an attempt is made to calculate the basic parameters (hydraulic conductivities), using a single phase flow model.

COASTAL AQUIFER MODELS
Two single phase models are investigated and their results are compared to a complex variable density model. The first single phase flow model is a 3-D layered model which uses a depth dependent freshwater head along the sea boundary, (Iribar *et al*, 1997). The equivalent freshwater hydraulic head at elevation z above the datum is given by $h_f = (1+\alpha)h - \alpha z$ where $a = (\rho - \rho_f)/\rho_f$ and h is the head (Guo & Langevin, 2002), (ρ is saline groundwater density and ρ_f is freshwater density). This boundary condition allows reversing of flow direction from the sea towards the land at the lower parts of the aquifer.

The second flow model is based on the sharp interface model described in Mantoglou *et al* (2004), which is based on a 2D Strack solution.

The coupled fluid flow – mass transport model is governed by the following equations (Diersch & Kolditz, 1998), ($i, j = 1,2,3$, and Einstein summation convention is used):

$$S_h \frac{\partial h}{\partial t} + \frac{\partial q_i}{\partial x_i} = Q_\rho + Q_{EB}(C), \quad \text{(continuity equation)} \qquad (1)$$

$$q_i = -K_{ij} f_\mu \left(\frac{\partial h}{\partial x_j} + \frac{\rho - \rho_0}{\rho_0} e_j \right), \quad \text{(Darcy equation)} \qquad (2)$$

$$\frac{\partial}{\partial t}(nC) + \frac{\partial}{\partial x_i}\left(q_i C - D_{ij} \frac{\partial C}{\partial x_j} \right) - Q_C = 0, \text{(transport equation)} \qquad (3)$$

$$\rho = \rho_0 \left\{ 1 + \frac{\overline{\alpha}}{(C_s - C_0)} \left(C - C_0 \right) \right\}, \text{ (fluid density)} \qquad (4)$$

where h is the hydraulic head, q_i is the Darcy fluid velocity vector, C is concentration of salt, S_h is specific storage coefficient, Q_ρ is a fluid source/sink, Q_c is contaminant mass source/sink, Q_{EB} is a term related to Boussinesq approximation (see Diersch & Kolditz, 1998), K_{ij} is the aquifer hydraulic conductivity tensor, f_μ is a constitutive viscosity relation function, e_j is the gravitational unit vector, ρ, ρ_0 are the fluid and reference fluid density respectively, n is the aquifer porosity, D_{ij} is the hydrodynamic dispersion tensor, and C_0, C_s are reference and maximum concentration, respectively. For each time step, the coupled system of flow and transport equations is solved numerically and the resultant concentration is used to calculate the density and Darcy velocity. Changes of viscosity are not considered here and it is assumed that $f_\mu = 1$. A constant mass concentration $C(x_i, t) = C_s$ and a similar head distribution $h_f = (1+\alpha)h - \alpha z$ described above are used at the saltwater boundary. The differential equations are solved numerically using FEFLOW package based on finite elements.

RHODES ISLAND CASE STUDY

The aquifer is located at the northern part of Rhodes Island and is of considerable size ($400km^2$). The aquifer geology is characterized by a complex geological and hydrolithological structure. Figure 1 shows the aquifer location along with a piezometric map produced by the variable density model as discussed below. Since the aquifer is quite large, the area within the frame is magnified in the following figure, to provide a more detailed preview of the final results. The dominant tectonic unit of the studied area consist of gravely-sandy, marly-sandy and conglomerate facies, while some areas consist of psephitic, psammitic and pelitic clastic deposits, and of bioclastic limestone. A limestone formation appears at the central region of the aquifer with a general NE – SW direction, due to a rift zone action.

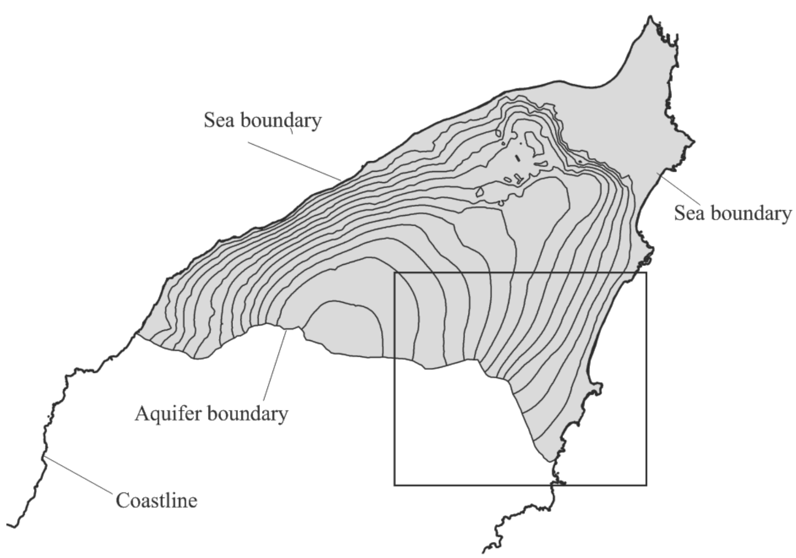

Figure 1. Rhodes Island aquifer with a piezometric map.

Due to lack of sufficient borehole data, the aquifer depth is not known exactly. For this reason a sensitivity analysis is performed for aquifer depths of 100m, 120m and 150m indicating a strong dependence of the results on the aquifer depth. For the current study the aquifer depth is assumed at 100m below sea level. Further field study would provide more data regarding the aquifer geometry.

The aquifer hydraulic conductivity is first calibrated against historic hydrological and piezometric data. The aquifer area is divided into several small hydrological basins and a uniform recharge is assigned in each basin, recommended by previous studies. The 3-D single phase model discussed above, based on vertically distributed freshwater head along the sea boundary, is selected for estimation of hydraulic conductivities. A zonation parameterization and the PEST algorithm are utilized to estimate the hydraulic conductivity values. Based on hydrolithologic data the aquifer is divided into six zones. Measured piezometric data are used to perform calibration. The calibrated model is able to follow the measured data very well.

Using calibrated hydraulic conductivities, a comparison between the 3-D single phase flow model, the 2-D sharp interface model of Mantoglou *et al* (2004) and the 3-D variable density model is performed next. The values of the remaining aquifer parameters required by the 3-D variable density model are obtained from previous studies and literature. The final simulation results are shown in Figure 2, and depict an almost identical piezometric head distribution for the three models.

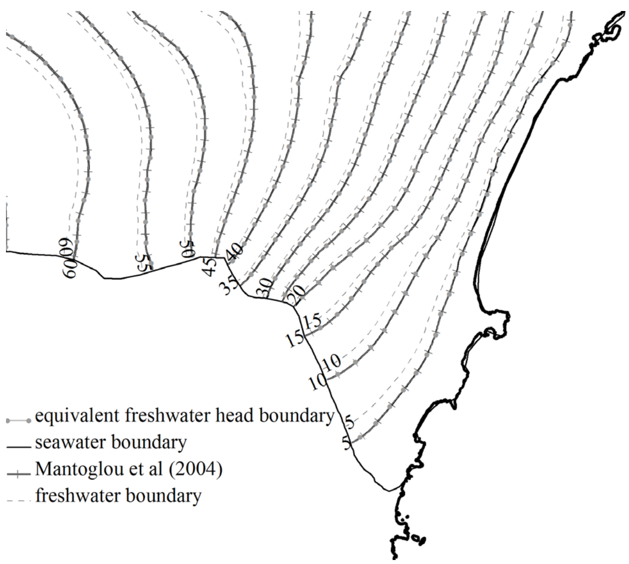

Figure 2. Comparison of piezometric heads produced by different models

Notice that some modellers use simple 2-D single phase flow models using a freshwater boundary condition at the sea. This results in considerable decrease of hydraulic heads, since a reduced resistance is imposed on freshwater discharge to the sea. In order to illustrate this, Figure 2 compares the results of the three modelling approaches described above, to the simplified 2-D single phase model. Notice that while the three modelling approaches presented here produce essentially similar hydraulic heads, the 2-D model based on freshwater boundary condition produces significant error.

DISCUSSION AND CONCLUSIONS

A 3D variable density model is developed for a Rhodes Island aquifer and compared to a 3-D single flow model and a sharp interface model. The results indicate that in this aquifer, which is of considerable size and the transition zone is expected to be relatively narrow, the piezometric head of the aquifer depends mainly on head boundary conditions, while transport processes can be simplified except for a narrow zone near the sea. A 2-D model on the other hand, based on freshwater boundary condition produces significant error. Undergoing field work will provide more data concerning the aquifer geometry and parameters, in order to improve these models.

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