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Coastal Aquifer Response in Drought Scenarios

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Abstract: The encroachment of seawater intrusion in coastal aquifers under drought conditions is examined in the current work. Two different approaches, 2D and 3D variable density models were used in order to quantify the dependence of aquifer yield on the recharge rate in dry years. For each scenario maximum pumping rate was calculated under the constraint that the chloride concentration would not exceed 100mg/l. Furthermore, a sensitivity analysis was performed regarding the effect of vertical hydraulic conductivity on maximum pumping rate potential. The results indicated a nonlinear relationship between the optimal pumping rate and the relative recharge as well as a significant decrease of available water for pumping in drought years.

Keywords: Variable density, seawater intrusion, drought.

1. INTRODUCTION

In many areas the productive potential of surface water is limited and this happens to be a common case for islands and coastal regions where availability in appropriate quality and quantity for potable water relies exclusively on groundwater resources.

In the light of a long-term and sustainable management of groundwater resources is of crucial importance to predict accurately the response of this complex physical system from planned activities. Often, due to intensive exploitation of fresh groundwater in coastal aquifers the established balance between fresh and sea water is reversed resulting in a large-scale inland saltwater intrusion.

The dominant factors of seawater intrusion are the flow regime above the intruding wedge, the variable density of fluid and hydrodynamic dispersion. Governing equations of flow and salinity transport have been developed, based on simplified or more complex conceptual models. A significant number of journal papers on the subject have been published. Mathematical models for saltwater intrusion in coastal aquifers were reviewed by Bobba (1993). The methods for simulation of seawater intrusion can be grouped into two broad categories: sharp interface and variable density models where a wide interface zone separates the two fluids.

Cheng and Ouazar (1999) and Mantoglou (2003) presented analytical solutions based on Ghyben-Herzberg, Glover (1964) and Strack (1976) solutions. Mantoglou *et al.* (2004) developed a sharp interface model and applied it in a pumping optimization problem. Essaid (1999) used a sharp-interface model to simulate a multilayered coastal aquifer system.

More complex variable-density models consider the transport processes occurring in the mixing zone and were applied in some cases (Huyakorn *et al.*, 1987, Sherif *et al.*, 1990 and Gambolati *et al.*, 1999). Volker and Rushton (1982) compared dispersive and sharp-interface modeling approaches, while Bear (1999) presented conceptual and mathematical models for both sharp-interface and variable density approximations. Mehnert and Jennings (1985) examined the effects of salinity-dependent changes in hydraulic conductivity on saltwater intrusion. The well-known Henry's problem was used as a benchmark by some researchers for testing the adequacy of density-dependent groundwater flow models (Segol *et al.*, 1975, Voss & Souza, 1987, Croucher & O'Sullivan, 1995 and Simpson & Clement, 2004).

Most of the papers mentioned above have focused mainly on the distribution of chlorides in an aquifer, using factors such as the position of the saltwater front or the thickness of the saltwater-freshwater transition zone. Simmons *et al.* (2001) examine the critical role of heterogeneity of porous media in variable-density groundwater flow and solute transport.

The encroachment of saltwater in large-scale aquifers was examined by Fan *et al.* (1997) and Ghassemi *et al.* (1996). Langevin *et al.* (2005) combined a surface-water flow and transport code (SWIFT2D) with a variable-density groundwater code (SEAWAT) to create an integrated code, which was applied in a Florida aquifer. Langevin (2003) applied a 3D variable-density model in Biscayne-Bay of Florida in order to calculate the submarine groundwater discharge. In this application Langevin used a specified concentration along the sea boundary of Biscayne-Bay aquifer as a base case. Alternate mixed boundary conditions were also proposed in order to simulate recirculation procedures within the aquifer near the sea boundary, which differentiated the final results significantly. Diersch and Kolditz (1998) made a thorough analysis of coupled groundwater flow and salt transport. They introduced a constraint on the boundary conditions, based on budget analysis along the boundaries. The budget analysis is exclusively related to the convective mass fluxes, whose direction is unambiguous. Smith (2004) also used a complex boundary condition on the sea boundary in order to quantify the submarine groundwater discharge.

Under the circumstances described above, managers are usually forced to come up with reasonable and efficient suggestions in questions related to the number of wells that should be installed in the region, their pumping rates and their positions without ignoring the important aspect of the annual replenishment of the aquifer. This management procedure constitutes a challenging task as additional complexity arises due to conflicting objectives according to each scenario. Under this acknowledgement, combined use of numerical models and optimization techniques are required. Very often the purpose of optimization is to maximize the total pumping rate of a number of wells while taking into account the control of saltwater intrusion into the aquifer (Mantoglou & Papantoniou, 2008). Several authors have examined the pumping optimization task for known well locations such as Gorelick et al (1984), Wang and Ahlfeld (1994). Mantoglou et al (2004) based on the sharp interface model and a 2D Strack solution developed a method of assessing the optimum pumping rates of coastal aquifers based on nonlinear optimization and evolutionary algorithms. Mantoglou and Giannoulopoulos (2004) examined the coastal aquifer sensitivity on recharge rate under drought conditions, using optimization methods to define the aquifer sustainable yield. Mantoglou and Papantoniou (2008) suggested an optimal design of pumping networks in coastal aquifers by optimizing the locations of wells and pumping rates with two different methodologies of simultaneous and two-stage determination of the decision variables.

2. VARIABLE DENSITY MODELS IN COASTAL AQUIFERS

Three – dimensional isothermal flow and salt transport in coastal aquifers is governed by the following equations (Diersch, 1988, 1998), ($i, j = 1,2,3$, and Einstein summation convention is used).

$$\frac{\partial}{\partial t}(n\rho)+\frac{\partial}{\partial x_i}(\rho q_i)=\rho Q_\rho, \tag{1}$$

(continuity equation)

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

(Darcy equation) (2)

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

(transport equation) (3)

$$\rho = \rho_0 \left\{ 1 + \frac{\overline{\alpha}}{C_s} C \right\}, \quad (4)$$

(fluid density)

where h is the hydraulic head defined by $h = {}^{p}\!/_{\rho_0 g} + z$, where p is pressure, ρ_0 is density of fresh water and z is the vertical coordinate, q_i is the Darcy fluid velocity vector, C is concentration of salt, S_h is specific storage coefficient (compressibility), Q_ρ is a fluid source/sink, Q_c is contaminant mass source/sink, K_{ij} is the aquifer hydraulic conductivity tensor, f_μ is a constitutive viscosity relation function, e_j is the gravitational unit vector, ρ is the fluid density ($\rho \geq \rho_0$), 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. Since changes of viscosity are not considered here, it is assumed that $f_\mu = 1$.

For impermeable boundaries, the boundary condition is:

$$q_C(\mathbf{x}, t) = qC - D_{ij} \frac{\partial C}{\partial x_j} n_j = 0 \quad (5)$$

The last equation means that neither convective nor dispersive mass flux occur through this boundary. Regarding mass transport boundaries, a constant mass concentration in the saltwater boundary:

$$C(x_i, t) = C_s \quad (6)$$

is normally applied, where C_s is the concentration of seawater.

3. APPLICATIONS AND ANALYSIS OF RESULTS

The aforementioned variable density models are applied in two hypothetical aquifers of rectangular shape, for a profile model and a full 3D numerical model. Two different numerical codes are used, HydroGeoSphere and FEFLOW, respectively. In both cases, the maximum allowable pumping rate was tested in relation to the gradual decrease of the aquifer recharge.

3.1 2D Variable Density Model- Estimation of maximum pumping rate in 2-D vertical cross-section with an iterative procedure

In order to accomplish an iterative estimation method for the maximum rate of withdrawal of two pumping wells for a variable-density problem, a vertical cross section was simulated by the use of HydroGeoSphere, a numerical flow and transport model (Therrien, McLaren, Sudicky, Panday, 2005).

In the next diagram the conceptual model of the vertical cross-section problem is presented. On the west side of the domain the sea-boundary is applied while two pumping wells of fixed location are established. Uniform flux representing recharge was applied at the top of the cross-section.

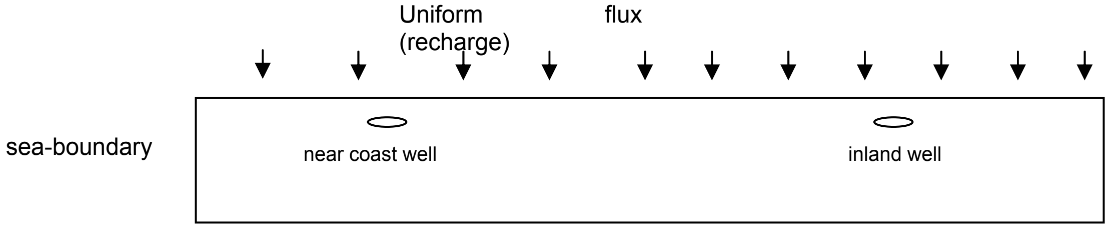

Figure 1: Conceptual design of the cross-sectional problem

At each modelling scenario recharge values were decreased in an extreme way in order to approximate intensive climate changes, for a simulation of 10 year-period. The post-processing of HydroGeoSphere results was implemented through MATLAB interface by imposing at each iterative step a small increase at the pumping rate of the inland well while keeping the well near the coast at constant rate equal to 10% of each applied recharge value. The iterative procedure was terminated for each case under the constraint that the well near the sea-boundary will not pump water with chloride concentration greater than 100mg/L. The ensemble of these results was analyzed in the way that Mantoglou and Giannoulopoulos (2004) present in a simulation – optimization methodology for water resources evaluation in coastal aquifers for a case study in Thira island. However, the iterative method that is presented in this current work is much more simplistic than the pure optimization method followed by Mantoglou and Giannoulopoulos (2004). The next diagram presents the trend-line that was attained for the following ratios Q_{total}/Q_{in} versus N_{in}/N_{ref}. Q_{total} is the maximum allowed sum of the well pumping rates, N_{in} is the recharge rate for each scenario, N_{ref} is the recharge value for the first scenario and Q_{in} is the total volumetric inflow rate.

It should be noted that in 2D vertical cross sections a pumping well behaves more like a ditch, as it cannot reproduce the circular water depression cone. To comply with this assumption single extraction nodes were used instead. Figure 2 demonstrate the seawater intrusion wedge in the reference scenario. Figure 3 depicts that in drought scenarios the aquifer yield is significantly reduced. The comparison between the linear model obtained from the reference scenario ratio and the model obtained from the iteration method indicates that a decrease of the recharge does not imply a proportional decrease of the total pumping rate. In particular, a 10% decrease of the ratio N_{in}/N_{ref} corresponds to a 26% reduction of total pumping, while in cases that extreme scenarios are simulated (N_{in}/N_{ref} less than 0.8) the percentage reduction of total pumping exceeds 50%.

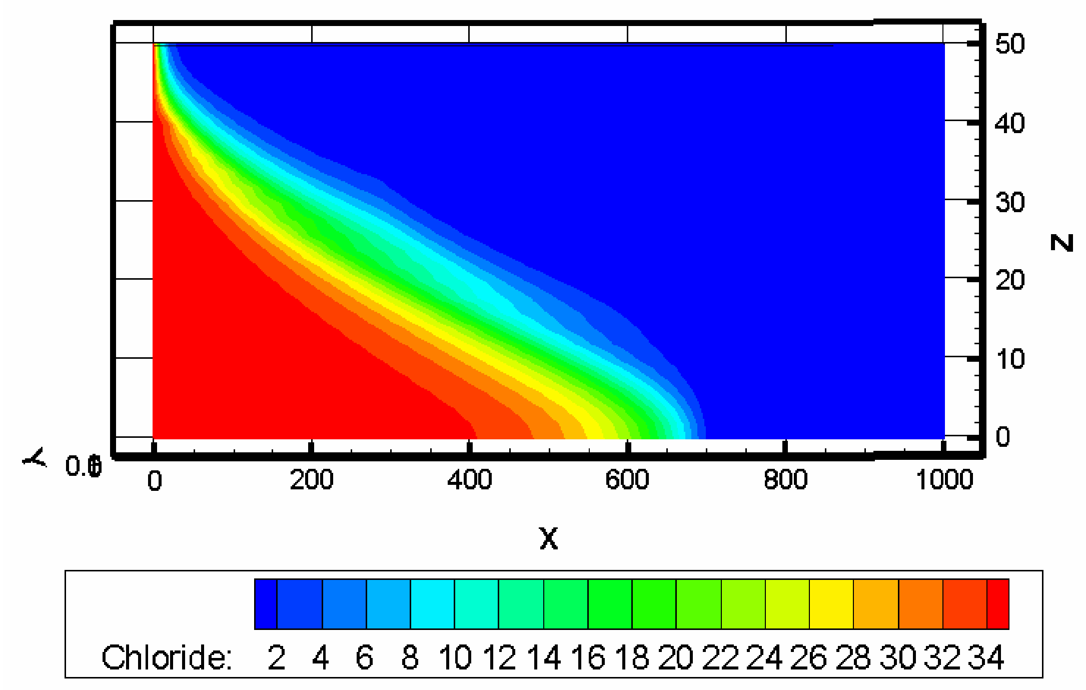

Figure 2: A vertical cross section example of seawater intrusion with two pumping wells.

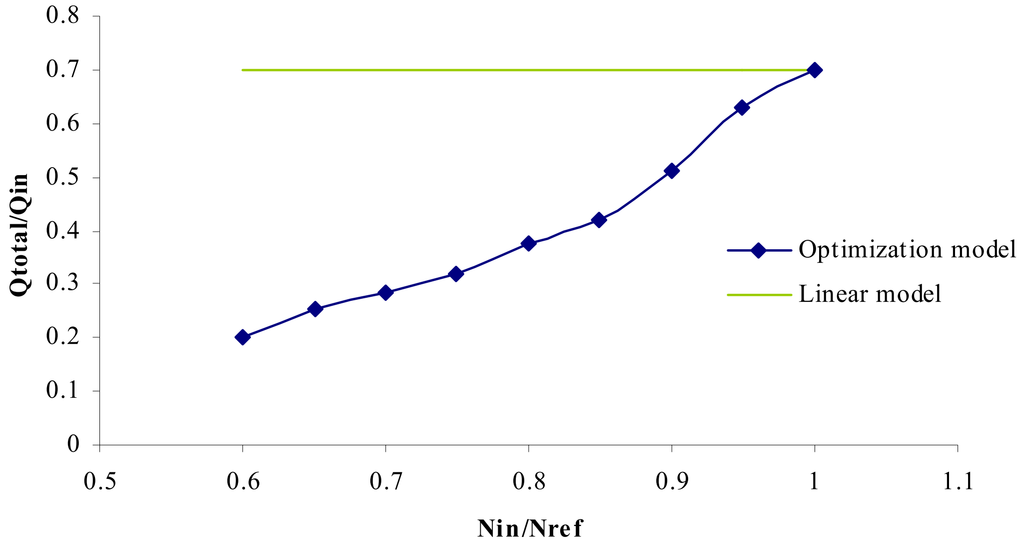

Figure 3: Trend-line for nine decreasing recharge scenarios.

3.2 3D Variable Density Mode l- Estimation of maximum pumping rate in several recharge scenarios

The 3D variable density model was applied to a hypothetical rectangular shape aquifer (Figure 4), with L=1000m, B=500m and d=50m. The B×d vertical plane represents the sea boundary. The aquifer is considered to be unconfined and anisotropic. The inland aquifer boundary and the aquifer bottom are considered impermeable. The basic problem parameters are included in Table 1. A uniform recharge is considered along the entire aquifer surface. An effort to generate credible initial conditions has been made through simulation of groundwater flow for very long periods without pumping.

Table 1: Basic simulation parameters

Parameters	
Kx	10m/d
Ky	10m/d
Kz	0.1m/d
Longitudinal dispersivity	5.0m
Transverse dispersivity	0.5m
Density ratio	2.5×10^{-4}

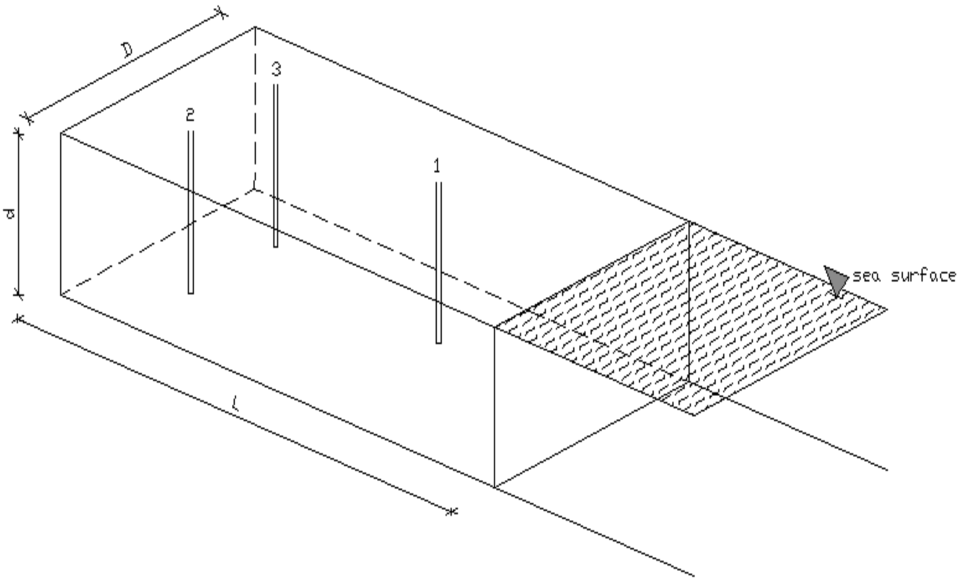

Figure 4: The examined hypothetical aquifer. The numbers represent the locations of the wells

The aquifer is pumped by three pumping wells located at coordinates (x,y)= (700,250), (150,150), (150,350). The first one, which is located closer to the sea boundary, is pumped with a constant pumping rate of $Q_1 = 10m^3/d$. The other two wells are pumped with the same rate. An iterative procedure is then utilized to maximize the total pumping rate for several recharge scenarios. A chloride concentration of 100mg/l in the first well is used as the stopping criteria of the procedure. A recharge rate of 182mm/year is used as a reference recharge. Then a 5% reduction in the recharge is applied in each of the following scenarios, until a total 40% reduction, in order to test the aquifer reaction in drought conditions. The aforementioned variable density model is developed in FEFLOW, which is a finite element based software package. An indicative 3D representation of the saltwater intrusion wedge is depicted in Figure 5.

Let Q_{total} represent the maximum pumping rate, Q_{in} represent the total volumetric inflow rate, N_{in} represent the aquifer recharge and N_{ref} represent the reference recharge rate. Then the change in the maximum pumping Q_{total} is examined with respect to the relative recharge N_{in}/N_{ref} . The results are included in Table 2 and plotted in Figure 6. This Figure depicts a strong dependence of the ratio Q_{total}/Q_{in} on the relative recharge rate N_{in}/N_{ref} . In particular, a reduction in the relative recharge reduces significantly the maximum allowed pumping rate in a non proportional way. In extreme drought scenarios the productive potential of the aquifer is one third of the linear model prediction.

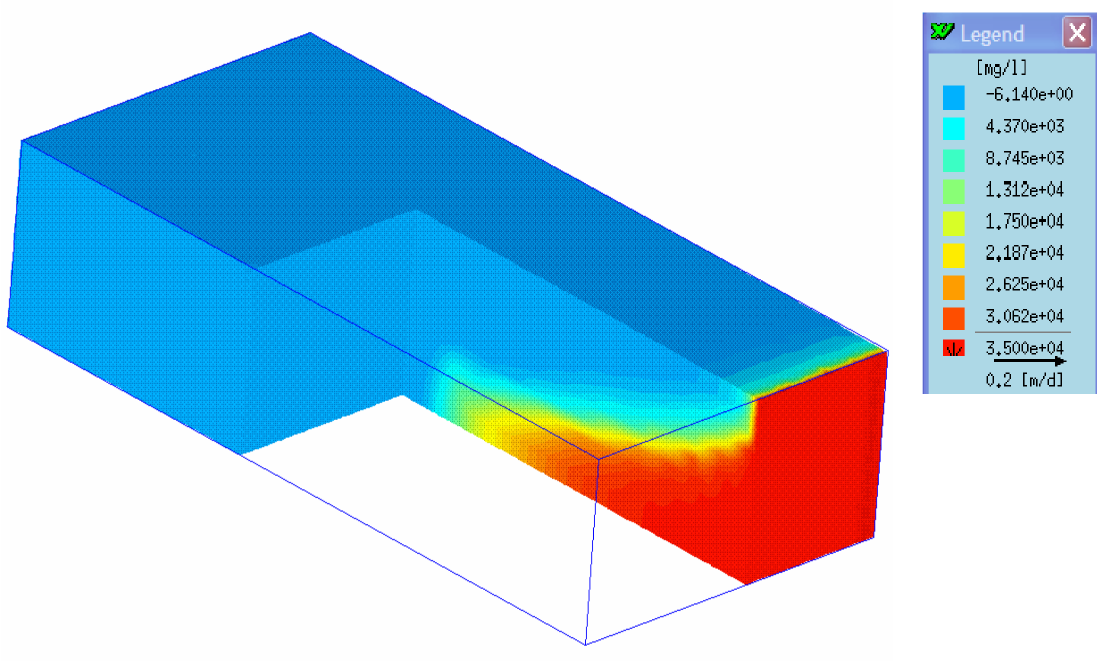

Figure 5: Saltwater intrusion wedge in the examined aquifer

Table 2: Simulation results for optimal pumping rates in several recharge scenarios.

N_{in} / N_{ref}	Q_{total} / Q_{in}
0.60	0.15
0.65	0.18
0.70	0.26
0.75	0.34
0.80	0.39
0.85	0.45
0.90	0.50
0.95	0.56
1.00	0.61

Several simulations with different aquifer parameters indicated a strong dependence of the total pumping rates on the vertical hydraulic conductivity value. For a vertical hydraulic conductivity value of $K_z = 10 m/d$ a significant reduction in maximum pumping rate is observed (Figure 6), which exceeds 40% in some recharge scenarios.

Based on the reference scenario results several time dependent simulations were performed. In general, time dependent simulations provide better approximations of the real system since they resemble better the underlying physical processes. On the other hand the CPU time required to complete the simulations increases significantly. The reference scenario recharge was uniformly distributed over a three month time period (December-January), as depicted in Figure 7. The optimized total pumping rate for this scenario was distributed based on the monthly water consumption evidence by some Greek island local communities (Figure 8). It should be noted that periods of high water consumption coincide with those of low recharge.

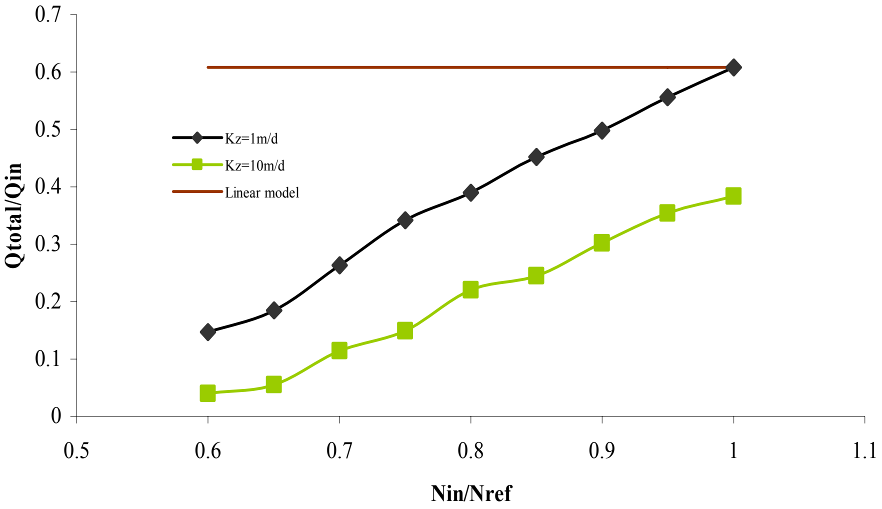

Figure 6: Dependence of aquifer yield on the recharge rate in dry years.

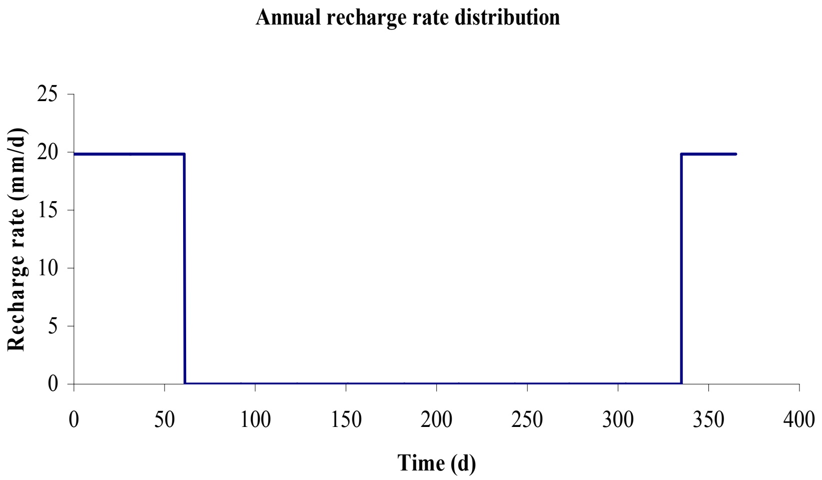

Figure 7: Annual recharge rate distribution based on simplified Greek island climate evidence

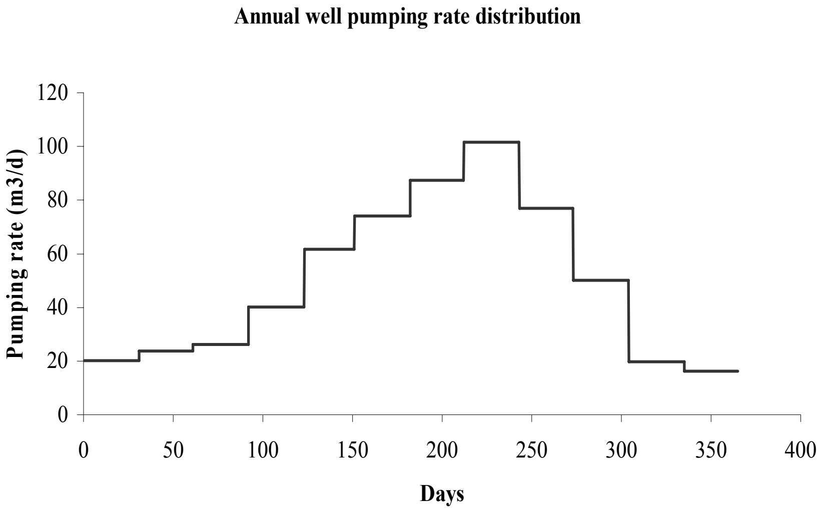

Figure 8: Annual well pumping rate distribution based on Greek island evidence

The results show fluctuations of hydraulic head during the year, which at some locations of the aquifer exceeds 1m. Chloride concentration showed an increase of the transition zone size compared to the steady case. A significant increase in mass concentration in the first pumping well was also observed in the case of time-dependent parameters. Figure 9 depicts the evolution of chloride concentration for the reference recharge scenario over a twenty year pumping period. In particular, the chloride concentration was approximately 300mg/l at the end of the simulation period, which is almost three times the maximum concentration limit used in the optimal pumping rate estimation. Figure 10 depicts the decrease of available water for pumping for the transient simulation.

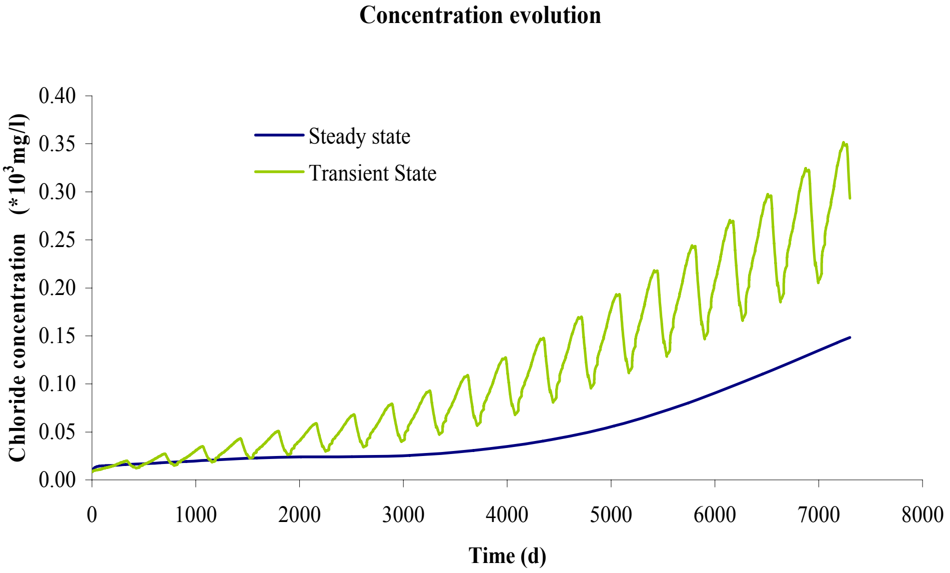

Figure 9: Evolution of the chloride concentration for steady state and transient state

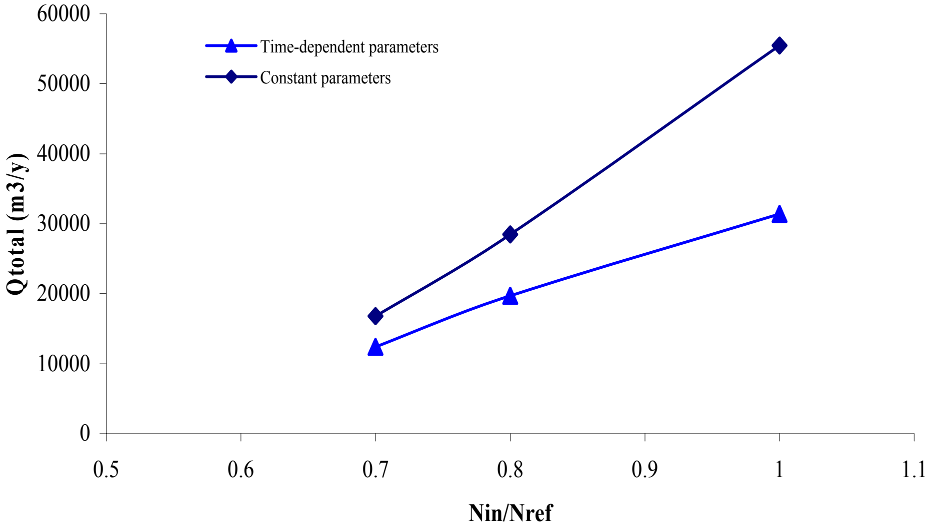

Figure 10: Comparison of maximum pumping rates for constant and time-dependent recharge values

In general, variable conditions, such as pumping and recharging, tend to increase the thickness of transition zone, whereas steady flows decreases it. However, use of pumping management optimization modules based on variable density and time dependent flow and mass transport models is CPU intensive. Therefore, a safety coefficient should be used in the steady state pumping rate results in order to avoid an extended saltwater intrusion in the examined aquifer. Several simulations are required in order to quantify such a coefficient and determine its sensitivity in different aquifer parameters, such as the aquifer size and hydraulic conductivity.

4. CONCLUDING REMARKS

Variable density models were selected to simulate the flow and mass transport in coastal aquifers, instead of the widely used sharp interface approximation. Certain difficulties arise by coupling variable density models with optimization techniques, mostly due to the computational demands. However, in the current study simplified procedures were followed for the estimation of the maximum pumping rates, which allows for considering the dispersion zone of saltwater and freshwater. Results from both 2D and 3D variable density models indicate a significant expansion of seawater intrusion wedge and a reduction in the productive potential as recharge rates decrease. Although both trend lines produced by the two different approaches seem to follow a quite similar non proportional relationship, the 2D model allows for higher maximum pumping rates. Since 2D approach ignores the transverse flow towards the wells, any results should be considered not so close to physical reality. However, due to its dimensionality vertical cross section model simplifies the use of iterative methods by reducing the computational effort comparing the 3D variable density model. In addition, anisotropy ratios of hydraulic conductivity and time distribution of recharge and pumping are introduce a notable uncertainty in the final results. It should be noted that none of the above results correspond to the sustainable yield of the aquifer, but provide an indication of the evolution of productive potential in dry climate conditions. In general, despite the limitations that pertain to both approaches, what was clearly evident in the present study is the non-linearity between pumping rates subject to certain constraints and aquifer recharge. Further study should include advanced optimization techniques to estimate the sustainable yield in more complex well fields under drought scenarios.

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