Using a computational optimization tool for the management of an aquifer at Kalymnos island in Greece

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ABSTRACT

A generic operational tool for the optimal management of coastal aquifers is applied to a real unconfined coastal aquifer in the Greek island Kalymnos. The models suite makes a combined use of a numerical model that predicts the seawater intrusion due to flow perturbations and of the optimization method of Genetic Algorithms. The presented management scenarios are based on the hydrodynamic control of seawater intrusion due to the operation of a network of productive wells and the seasonal use a of a recharge canal which is an alternative method for increasing aquifer sustainable productivity.

INTRODUCTION

Overexploitation of groundwater in coastal aquifers has upset the balance between freshwater and seawater potentials, causing landward movement of seawater into freshwater aquifers. The intensive pumping of coastal aquifers, especially during summer months, results to saltwater intrusion which decreases aquifers efficiency beyond sustainability levels.

Models of salt and fresh water flow in coastal aquifers serve as important tools for assessing the extent of saltwater intrusion and for planning the rational exploitation of water resources (Dagan & Zeitoun, 1998). Two general approaches have been used to analyze saltwater intrusion in coastal aquifers: the disperse interface and the sharp interface. The present paper refers to the synthesis of a two-layer numerical model and the presentation of a generic solution algorithm, based on the second approach.

The combined use of the numerical simulation and of a stochastic optimization method, namely the method of Genetic Algorithms (GAs), leads to the optimal pumping rates of production wells. Two scenarios are examined; the first is the hydrodynamic control of seawater intrusion by the operation of eight production wells and the second is the additional use of a recharge canal, a hydraulic technique that aims to restrain the intrusion of the salt wedge towards the wells.

FORMULATION OF THE MATHEMATICAL MODEL

The formulation of the mathematical model is based on the equilibrium equation and the mass balance, subject to two simplifying assumptions (Koutitas, 1983 and 1988); the assumption of two immiscible layers of salt and fresh water implying a sharp interface between the two layers and the assumption known as “Dupuit” assumption, referring to the hydrostatic pressure distribution in the two layers (assumption of nearly horizontal flow) and the consideration of the depth- mean seepage velocities in each one.

In case of quasi-horizontal flows assuming hydrostatic pressure distribution, the seepage velocities are estimated by the Dupuit law and the governing equations can be written for the two layers separately, characterized by the densities ρ_f and ρ_s for the upper and the lower layer respectively, and the deriving dimensionless magnitude $\Delta\rho/\rho_s = (\rho_s-\rho_f)/\rho_s$.
Thus for the upper layer the mass balance equation, taking in consideration the Dupuit law, is expressed by the Boussinesq equation which for an unconfined aquifer is written as:

$$\frac{1}{n}\frac{\partial h_f}{\partial t} = \frac{1}{\rho_f g}\left[\frac{\partial}{\partial x}\left(K_x\left(h_f\frac{\partial p_f}{\partial x}\right)\right) + \frac{\partial}{\partial y}\left(K_y\left(h_f\frac{\partial p_f}{\partial y}\right)\right)\right] \pm q \qquad (1)$$

The same approach for the lower layer leads to the equation:

$$\frac{1}{n}\frac{\partial h_s}{\partial t} = \frac{1}{\rho_s g}\left[\frac{\partial}{\partial x}\left(K_x\left(h_s\frac{\partial p_s}{\partial x}\right)\right) + \frac{\partial}{\partial y}\left(K_y\left(h_s\frac{\partial p_s}{\partial y}\right)\right)\right] \pm q \qquad (2)$$

Where n is the porosity, p is the pressures in the two layers and the term q describes the local sinks or sources distributed along the aquifer. (Arvanitidou *et al.*, 2010).

OPTIMIZATION MODEL

The optimization technique that is used is the stochastic method of Genetic Algorithms. This method is a mathematical imitation of a biological process, namely that of the evolution of species, based on the Darwin's theory about the survival of the fittest members of a population in a hostile environment. The evaluation function is used for the decision of possible scenarios that ensure the sustainable exploitation of a coastal aquifer by the hydrodynamic control of a pumping network and a recharge canal. These scenarios comprise the operation, or not, of eight production wells, during spring-summer periods, located along a coastal aquifer and their pumping rates, as well as the optimum location of a recharge canal parallel to the coastline, forming the discrete decision variables. The objective of the evaluation function is the maximum total pumping rate of the production wells (Qs). A penalty is imposed when saltwater penetrates a production well (Katsifarakis & Petala, 2005). So the application or not of the penalty requires solution of the two-phase flow simulation model.
Then, the fitness value of each solution is given as:

$$VB = \sum_{i=1}^{8} Q_i - PEN \text{, where } PEN = 2\sum_{i=1}^{k} Q_i \qquad (3)$$

Q_i is the pumping rate of each production well and PEN is a penalty, imposed if salt water intrudes to any of the production wells (k is the number of the wells where saltwater wedge arrives). This is checked by means of the stratified flow simulation model. The main operators of the GAs in this paper are: (a) selection, (b) crossover and (c) mutation. The elitist approach is used in order to ensure the maintenance of the best solution through the successive generations.

APPLICATION TO THE AQUIFER AT VATHY ON KALYMNOS ISLAND

The above combined optimization model is applied to an unconfined aquifer at Vathy in the Greek island of Kalymnos. According to Mantoglou *et al*. (2004) the aquifer has uniform Hydraulic conductivity K=100m/day, n=0.2, $\Delta\rho/\rho$=0.0025, an approximately rectangular shape

7000m x 3000m and the thickness from the base of the aquifer to the sea surface is taken as d=25m. The recharge rate at the higher elevations of the aquifer is N=150mm/year distributed over an area of $A=9Km^2$. Thus the annual recharge volume at the mountainous region of the aquifer is $V = N \times A = 1.35 \times 10^6 m^3 / year$, producing a horizontal discharge per unit width of the aquifer $q=V/B=1.23m^2/day$. The sea boundary constitutes a constant head boundary, whereas the north and south boundaries are assumed impermeable. Figure 1 shows the shape and the boundaries of the aquifer.

Two scenarios are examined and presented; the first optimization task is to find the maximum total flow rate of a pumping network that can be safely pumped by a system of eight candidate wells. The maximum total pumping rate that results from the optimization model is $Q_{total}=7200m^3/day$. Figure 2 plots the seawater toe location due to the operation of four wells. The seawater wedge moves more than 3.5Km inland without reaching any of the production wells W_5, W_6, W_7 and W_8. Figure 3 plots the fitness value of the best solution in each generation for the 1^{st} scenario. The convergence of the solutions reached from the 25^{th} generation.

In the second scenario, the pumping rates of the eight wells and the position of a recharge canal parallel to the coast are the decision variables. The use of a recharge canal parallel to the coast, during autumn-winter periods enriches the aquifer and forms a fresh water barrier in order to prevent saltwater intrusion. The position of the recharge canal, with a pumping rate equal to $Q_{canal}=1000m^3/day$ and length l=1000m, is examined, as a hydraulic technique that aims to restrain the intrusion of the salt wedge towards the wells. The best solution places the recharge canal 4Km from the coast and the production wells have a total pumping rate $Q_{total}=7400m^3/day$. The seawater wedge retreats seaward and the six production wells are protected (Figure 4).

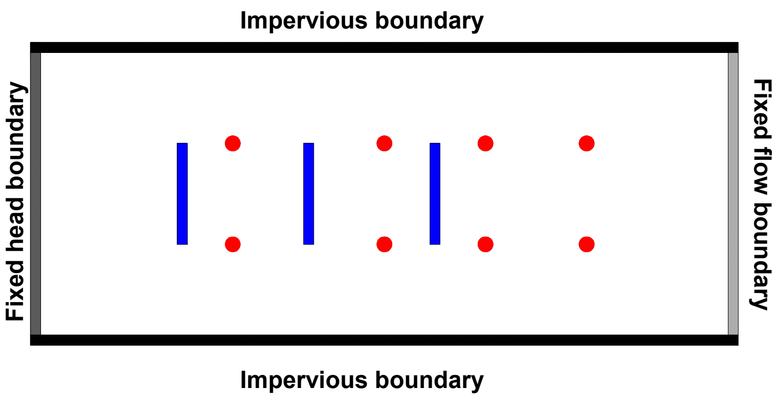

Figure 1. Boundary conditions for the rectangular aquifer. The dots are well locations with coordinates: $W_1(2000,1000)$, $W_2(2000,2000)$, $W_3(3500,1000)$, $W_4(3500,2000)$, $W_5(4500,1000)$, $W_6(4500,2000)$, $W_7(5500,1000)$, $W_8(5500,2000)$. Lines are the possible positions for the recharge canal.

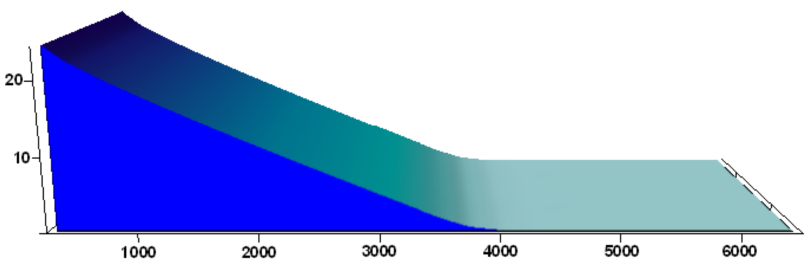

Figure 2. Sea water wedge for the optimum solution of the 1^{st} scenario. The pumping rates of the network are: $Q_1=0m^3/day$, $Q_2=0m^3/day$, $Q_3=0m^3/day$, $Q_4=0m^3/day$, $Q_5=1800m^3/day$, $Q_6=1800m^3/day$, $Q_7=1800m^3/day$, $Q_8=1800m^3/day$. $Q_{total}=7200m^3/day$

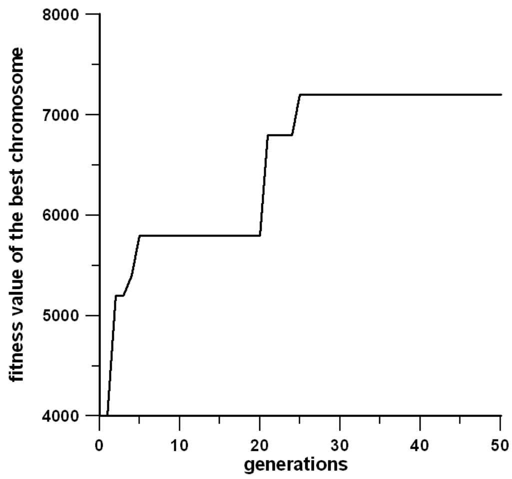

Figure 3. Maximum fitness value, for the 1st scenario, as a function of generation number for 50 generations and population size equal to 40.
Set of parameters in GAs: population size PS 40; crossover probability CRP 0.5; mutation probability MP 1/SL=1/8 or 1/9, where SL is the length of the chromosome, number of generations NG 50; selection constant KK, 3.

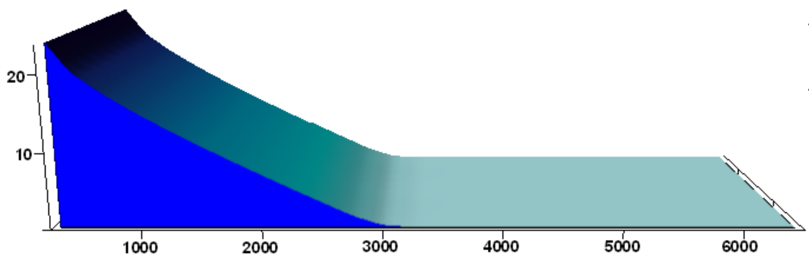

Figure 4. Sea water wedge for the optimum solution of the 2nd scenario. The canal position is 4Km far from the coast.
The pumping rates of the network are:
Q_1=0m^3/day, Q_2=0m^3/day,
Q_3=1200m^3/day, Q_4=1400m^3/day,
Q_5=1800m^3/day, Q_6=600m^3/day,
Q_7=800m^3/day, Q_8=1600m^3/day
Q_{total}=7400m^3/day

DISCUSSION AND CONCLUSIONS

The presented computational model applied to the aquifer at Vathy on Kalymnos island targeting the higher sustainable yield of the aquifer. Results show that proper pumping strategies can increase the total pumping rates of production wells and ensure the safe operation of coastal aquifers. This optimization model can propose different management scenarios based on the operation of pumping networks and of other hydraulic techniques (recharge canals or scavenger wells) for the hydrodynamic control of seawater intrusion. Thus, it can be used as a decision making tool for the integrated management of coastal aquifers.

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