Coastal aquifer management under drought conditions considering aquifer spatial variability

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Abstract The problem of pumping optimization of coastal unconfined aquifers is investigated. The Sequential Quadratic Programming (SQP) optimization method is combined with a numerical flow model based on the sharp interface assumption and Ghyben-Herzberg approximation. The objective is to maximize the total pumping rate, considering aquifer spatial variability and drought conditions due to climate changes, while protecting the aquifer from seawater intrusion. Using Monte-Carlo simulation, optimal pumping rates were calculated for different statistical properties of hydraulic conductivity and for various drought recharge scenarios. The results indicate that the maximum allowed pumping rates are significantly affected by the variance and correlation length of hydraulic conductivity random fields while recharge reduction leads to a significant reduction of maximum pumping.

Key words groundwater; seawater intrusion; Monte-Carlo

INTRODUCTION

Optimal management of coastal aquifers constitutes a challenging task in semi-arid Mediterranean islands and regions. Increased water needs and low recharge rates, especially during summer, threaten the sustainability of groundwater quantity and quality. Therefore, it is important to develop appropriate simulation and optimization models for calculating maximum pumping rates. This problem has been extensively investigated in the literature (Gorelick, 1983; Wang & Ahlfeld, 1994; Gordon *et al*., 2000; Mantoglou, 2004; Park & Aral, 2004; Mantoglou, 2008; Kourakos & Mantoglou, 2009). A common approach for simulation of seawater intrusion in coastal aquifers, is based on the sharp interface approximation and the Ghyben-Herzberg relation (Bear, 1979; Essaid, 1990; Bear *et al.*, 1999; Cheng *et al*., 2000; Mantoglou, 2003). This approach is also adopted for this work.

The present paper investigates the effect of hydraulic conductivity spatial variability on coastal aquifer management. Hydraulic conductivity is assumed to be a 2-D random field and a Monte-Carlo simulation is used to quantify this effect. Then a reduction of recharge rates is examined in order to investigate the impact of drought conditions on the maximum pumping rates in the case of spatially variable soils.

MODELLING AND OPTIMIZATION METHOD

The conceptual flow model and the optimization framework are based on previous work by Mantoglou *et al.* (2004). The groundwater model setup is based on the sharp interface approximation and the Ghyben-Herzberg relation, assuming steady-state unconfined flow. The flow equations are expressed using the Strack’s potential (1976) and the governing flow equations are solved using a finite element numerical model based on HydroGeoSphere code. The application refers to a coastal aquifer of orthogonal shape as shown in Fig. 1 and it approximates a real aquifer at Vathi in the Greek island of Kalymnos. The objective is to maximize the total pumping rate while protecting the aquifer from seawater intrusion. Let the aquifer be pumped by n wells with rates Q; $i = 1, \ldots, n$, respectively. The coordinates of the wells (x_i, y_i); $i = 1, \ldots, n$ are assumed known.

The formulation of the optimization problem is expressed as follows (Mantoglou *et al.*, 2004; Mantoglou & Papantoniou, 2008):

$$\text{maximize:} \quad Q_{tot} = \sum_{i=1}^{n} Q_i \; ; \quad i = 1, \ldots\ldots, n$$

$$\text{subject to:} \quad \begin{aligned} &\varphi_i > 0 \\ &x_{ti}(Q_i) < x_{wi} \\ &Q_{i,\min} < Q_i < Q_{i,\max} \end{aligned}$$

where $Q_i \in R^n$ are the decision variables, φ_i represents the Strack potential and x_{ti}, x_{wi} express the distance from the coast of the toe and the well, respectively. The first set of constraints maintains the free surface of the aquifer above sea level by setting the potential φ_i at the well locations (x_i, y_i) larger than zero. The second constraint prevents the saltwater toe from reaching the wells, even when the flow potential remains positive. The objective function is linear, but the overall optimization problem is nonlinear, since the second set of constraints is nonlinear with respect to the decision variables. The Sequential Quadratic Programming (SQP) is used as an optimization method since it requires fewer iterations to converge and therefore less computational time compared to heuristic methods (e.g. genetic algorithms). This is important, considering the large number of the examined scenarios. SQP proved to be efficient for a small number of decision variables as in our case. In order to ensure that the global minimum was computed, some scenarios, especially those with the extreme high or low values of the objective function were re-examined, either with different initial conditions or with an alternative optimization method (genetic algorithm).

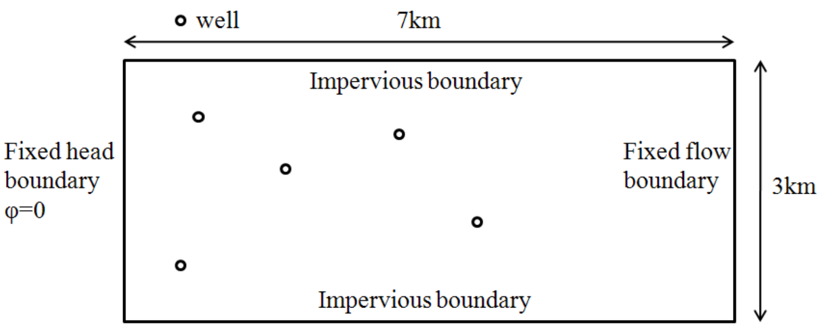

Fig. 1 Application in an aquifer of rectangular shape (see details in Mantoglou *et al*., 2004).

The hydraulic conductivity fields are assumed as stochastic random fields following a lognormal distribution with a mean value of log$K$ = 3 (m/day). Six different sets of values of statistical parameters of hydraulic conductivity were examined. Three sets of 100 isotropic random fields and three sets of 100 anisotropic random fields were simulated for 0.1, 0.2 and 0.3 variance of log$K$. The optimal pumping rates were calculated for each realization, using an optimization code developed in the MATLAB environment. The flow equation was solved during optimization for the Strack potential using HydroGeoSphere code. The results of Monte-Carlo optimization were compared to the pumping rates obtained by a uniform reference field with hydraulic conductivity equal to the mean of log$K$ = 3 (m/day).

Next, the above optimization methodology was utilized for reduced aquifer recharge compared to the reference recharge. This allowed for the investigation of the impact of possible climate changes on the maximum pumping rates in the case of spatially variable hydraulic conductivity.

RESULTS

Mean values of the total optimal pumping are calculated for each Monte-Carlo simulation-optimization scenario. They are compared to the optimization result corresponding to the uniform reference field which is 1792 m^3/day. The mean values in the six statistical patterns of hydraulic conductivity are lower compared to the optimal total pumping obtained from the uniform field. Specifically, for an increase in variance to 0.1, 0.2 and 0.3, the mean optimal total pumping for the statistical isotropic random fields is decreased to 1711, 1603 and 1516 m^3/day, respectively. Similar results are obtained in the case of statistical anisotropic random fields. For an increase in variance to 0.1, 0.2 and 0.3, the mean optimal total pumping is decreased to 1690, 1576 and 1461 m^3/day, respectively. .

However, it is noted that the maximum optimal pumping for particular realizations ranges from 22 to 42% higher than the value obtained from the uniform field depending on the variance. These extreme solutions correspond to realizations with a low hydraulic conductivity zone between the wells and the sea protecting the wells from seawater intrusion. Also, some realizations give zero maximum total pumping and correspond to cases where the second set of constraints is violated, even with no pumping. These solutions correspond to realizations with a high hydraulic conductivity zone between the wells and the sea, allowing seawater to reach the wells even with no pumping.

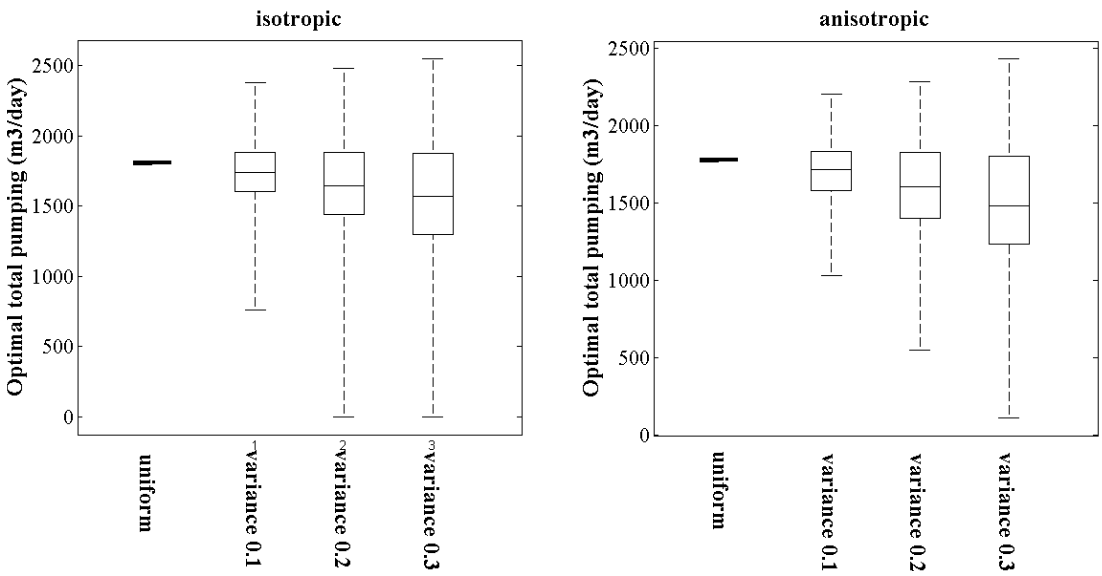

Fig. 2 Optimal total pumping for the reference uniform field and box plots of the optimal total pumping for the stochastic random fields.

Figure 2, illustrates the box plots for each optimal total pumping set obtained from the Monte-Carlo simulation. This diagram also indicates that as the random field variance increases, the distribution of the optimal pumping values exhibits a larger variance and larger extreme values. Note that the extreme low optimal total pumping is zero for both isotropic and anisotropic fields for large variance.

In general, a 4%, 12% and 18% reduction of the mean optimal total pumping is observed for the isotropic case as the field variance increases from 0 to 0.1, 0.2 and 0.3, respectively. For the case of statistical anisotropic random fields, increase of variance produced approximately a 6%, 14% and 22% reduction in the mean value of the optimal total pumping, respectively. This implies that the correlation length of the random fields affects the optimization results (in this work the direction correlation length ratio x:y was 3:1).

The above simulation–optimization method was utilized next in a management plan which assumes a reduction of the total aquifer recharge compared to the reference recharge. The reduction was applied to the uniform field and to the set of isotropic random fields with variance 0.1. Optimal total pumping results were obtained by reducing the reference recharge by 10%, 20% and 30%, respectively. In the case of the uniform field, a 10% decrease in the reference recharge leads to a 9% reduction in the maximum allowed pumping, while a 20% and 30% decrease in reference recharge correspond to an 18% and 27% reduction, respectively. Therefore a significant reduction in the maximum allowed pumping is expected under drought conditions.

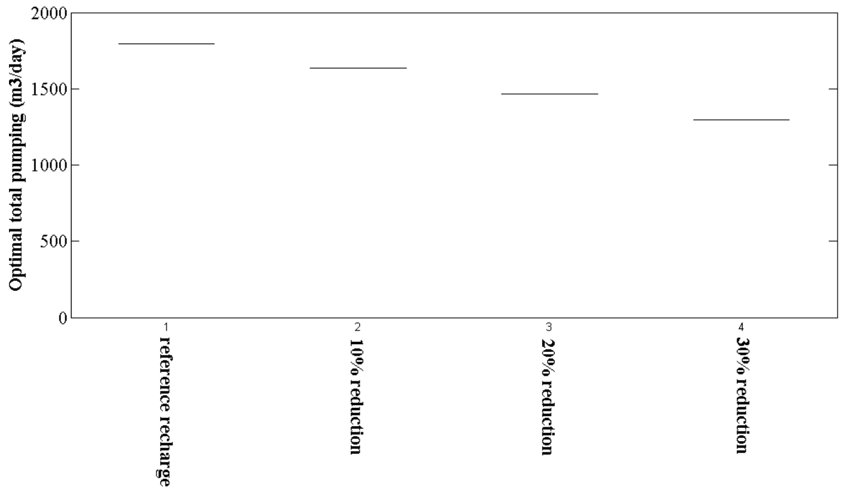

Fig. 3 Optimal total pumping obtained from the reference uniform field under drought conditions.

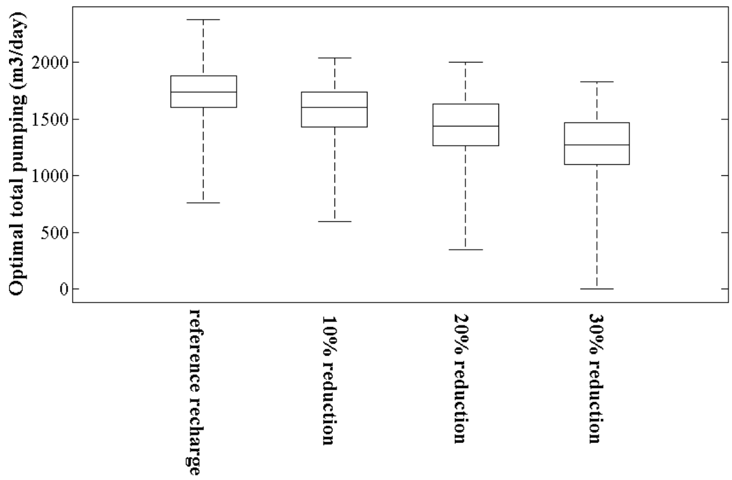

Fig. 4 Box plots of the optimal total pumping for the stochastic random fields with variance 0.1 under drought conditions.

Similar reductions in the mean maximum allowed pumping, are obtained from the isotropic random fields with variance 0.1. Again, a 10% decrease in reference recharge leads to a 9% reduction in the maximum allowed pumping, while a 20% and 30% decrease in reference recharge corresponds to an 18% and 27% in the maximum allowed pumping, respectively. These results are similar to the uniform case, however, there are certain random fields which exhibit a stronger reduction of optimal total pumping with recharge reduction. Figure 3 presents the optimization results for the reference uniform field, while Fig. 4 demonstrates the optimization results for the set of isotropic random fields with variance 0.1.

For all recharge reduction scenarios the maximum optimal pumping (Fig. 4) is higher than the total pumping obtained from the reference uniform field (Fig. 3). It is demonstrated in the box plot diagram that as recharge is further reduced, the distribution of the optimal pumping values exhibits a larger variance and larger extreme low values. Regarding the realization corresponding to the extreme low optimal pumping, the decrease in reference recharge by 10%, 20% and 30%

corresponds to a 21%, 54% and 99% decrease in the maximum pumping, respectively. Therefore the mean values of optimal total pumping cannot fully describe the optimization results of the different realizations as recharge is reduced. The distribution of the optimal pumping values appears to be less symmetrical as recharge reduction occurs.

CONCLUSIONS

A simulation–optimization methodology was applied in order to investigate the effects of aquifer spatial variability and drought conditions on the calculation of maximum total pumping in a coastal unconfined aquifer. The hydraulic conductivity fields are assumed to be stochastic random fields while a uniform conductivity field was also used in order to compare the optimization results with those obtained from the stochastic random fields. Monte-Carlo mean values for optimal total pumping were found to be lower than the optimal pumping obtained from the reference uniform field. The results also indicate that an increase of the hydraulic conductivity field variance leads to a decrease in the mean values of the optimal total pumping. Furthermore, the correlation length ratio of the generated random fields appears to affect the optimization solution.

The simulation–optimization methodology was applied in order to investigate the effect of decreasing the aquifer recharge due to climate changes on the optimization solution. While the mean optimal total pumping is reduced almost by the same proportion as the aquifer recharge reduction, a much stronger reduction was observed in the maximum allowed pumping for individual realizations of the random fields.

For a non-uniform hydraulic conductivity field, which is the case in real hydrogeological settings, extreme solutions are found depending on the existence of high or low conductivity zones across the aquifer. This implies that the mean optimal total pumping is not representative of the whole set of realizations.

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