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The value of hydraulic conductivity information for the optimal restoration of an over-exploited aquifer

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Abstract

A stochastic management tool is developed and applied in order to evaluate the worth of hydraulic conductivity data on the optimal restoration and quantitative management of the over-exploited aquifer of Lake Karla watershed in Greece. This tool consists of six models (one geostatistical, four simulation models and one management model) and combines the methodologies of: stochastic simulation-optimization, Bayesian analysis and the value of information analysis. The four simulation models (surface hydrology, reservoir operation, lake-aquifer interaction and hydrogeology) are interlinked in order to satisfy the needs of integrated simulation at the watershed scale. The heterogeneity and the lack of sufficient data of hydraulic conductivity create uncertainty on the hydraulic heads estimation. Monte Carlo realizations of hydraulic conductivity are being performed with the use of geostatistical tools and imported to the groundwater model to give multiple stochastic realizations of the aquifer. A Monte Carlo based optimization problem is then applied for each aquifer realization in order to determine the optimal aquifer's restoration management strategy. Optimal strategy has been defined the one that combines the maximum possible volume of extracted groundwater and the optimal well's position with the least financial cost, under the environmental constraint of restoring the aquifer water table. The hydrogeological uncertainty is being transformed into financial uncertainty through the optimization problem, as certain risks for the decision maker are being introduced. To avoid hydraulic head underestimation, a Bayesian decision analysis for the hydraulic conductivity data collection is being applied on each optimal solution. The worth of the new hydraulic conductivity data can be evaluated by quantifying the reduction of both hydrogeological and financial uncertainties. The results prove that there is a certain number of new hydraulic conductivity measurements up to which the profit by reducing financial uncertainty exceeds the measurement cost.

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Keywords: aquifer restoration; hydrogeological uncertainty; geostatistical approach; Monte Carlo simulation and optimization;

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1. Introduction

The combination of simulation and optimization techniques is the most appropriate method for groundwater management [1], as it takes into account the complex behavior of the groundwater system and determines the best management strategies [2]. This combination can be successfully achieved with the response matrix approach [3,4,5] regarding linear problems. The heterogeneity of the hydraulic conductivity parameter combined with the lack of relevant data, produce uncertainty in the simulation and thus in the optimization procedure, which creates in turn risks in decision making process [6,7,8,9,10,11]. To overcome this problem, the geostatistical approach has been widely applied for the stochastic simulation of the spatially variable hydraulic conductivity [12,13,14,15] generating equally probable Monte Carlo realizations. These realizations of hydraulic conductivity are imported to the groundwater model in order to create additional aquifer realizations. For the application of the selected optimization problem on the multiple aquifer's realizations, the Monte Carlo stochastic optimization approach [16] could be used so as to find the optimal management strategies that the decision maker can follow.

Nowadays, the success of a sustainable groundwater management plan depends on these strategies that will give the best growth-economic effect with the smallest possible cost. That's why many groundwater management studies, worldwide, incorporate financial factors in the optimization problems [17,18,19,20]. An innovative framework of applying optimum and sustainable strategies on groundwater management is the combination of stochastic optimization and the value of information analysis of the uncertain parameter [21]. Actually, the last is applied on every strategy that optimization procedure generated and reduces the parametric and financial uncertainty by collecting additional data from the field with the use of Bayesian updating [22].

This study proposes an innovative framework containing all the above mentioned methodologies for the quantitative management of an over-exploited aquifer. The novelty of this work is that a simulation system has been developed in order to study the problem at watershed scale satisfying the principles of integrated modelling and the fact that the innovative combination of stochastic optimization and the value of information analysis is applied at a real large scale aquifer targeting not only to an optimum and sustainable groundwater management, but also to water table optimum restoration.

2. Study Area

The study area is Lake Karla watershed, located in eastern Thessaly of central Greece (Fig. 1). It is one of the most productive agricultural regions of Greece, with lack of surface water, after 1962, when Lake Karla was drained [23]. Information about climate, hydrology and geology can be found in Sidiropoulos et al. [23]. The growth of agricultural, which is based on water demanding cultivations, with the lack of any water management practices has led to a significant water table drawdown. Because of the lack of an irrigation network, the covering of the irrigation needs has been done by groundwater with the use of private pumps, most of them illegal. Lake Karla's phreatic aquifer has an area of 500 km^2 and occupies the lower part of the basin with the altitude ranging from 45 to 90 m. It consists of medium permeable grainy sediments such sand and clay, which are located in great depths. The basement rock consists of impermeable marbles and schist [24]. The east boundary is a no flow boundary because of marbles and schist presences, but a medium hydraulic contact is taken place to the west with the adjacent aquifer. The inflows are the recharge from rainfall, the irrigation return and the west boundary hydraulic conduct. The outflows of the groundwater system are occurred from pumping wells covering water needs for irrigation, water supply, husbandry and industry. Irrigation needs consume almost the 98% of the groundwater extracted volume. The mean annual renewable water reaches up the 37.3 hm^3, while the mean annual extracted groundwater is about 131 hm^3. This status has led to 80 m water table drawdown on the south side of aquifer for the historical period 1987-2012 [25].