Journal of Hydrology (2007) **342**, 270–282

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jhydrol

Application of linear programming and differential evolutionary optimization methodologies for the solution of coastal subsurface water management problems subject to environmental criteria

Stefanos M. Karterakis [a], George P. Karatzas [a,*], Ioannis K. Nikolos [b], Maria P. Papadopoulou [a]

[a] *Department of Environmental Engineering, Technical University of Crete, Polytechneiopolis, Chania 73100, Greece*
[b] *Department of Production Engineering and Management, Technical University of Crete, Polytechneiopolis, Chania 73100, Greece*

Received 14 April 2006; received in revised form 8 May 2007; accepted 28 May 2007

KEYWORDS
Groundwater Modeling;
Linear programming;
Simplex method;
Coastal aquifer;
Fresh water;
Environmental criteria;
Evolutionary algorithms;
Differential Evolution

Summary In the past optimization techniques have been combined with simulation models to determine cost-effective solutions for various environmental management problems. In the present study, a groundwater management problem in a coastal karstic aquifer in Crere, Greece subject to environmental criteria has been studied using classical linear programming and heuristic optimization methodologies. A numerical simulation model of the unconfined coastal aquifer has been first developed to represent the complex non-linear physical system. Then the classical linear programming optimization algorithm of the Simplex method is used to solve the groundwater management problem where the main objective is the hydraulic control of the saltwater intrusion. A piecewise linearization of the non-linear optimization problem is obtained by sequential implementation of the Simplex algorithm and a convergence to the optimal solution is achieved. The solution of the non-linear management problem is also obtained using a heuristic algorithm. A Differential Evolution (DE) algorithm that emulates some of the principles of evolution is used. A comparison of the results obtained by the two different optimization approaches is presented. Finally, a sensitivity analysis is employed in order to examine the influence of the active pumping wells in the evolution of the seawater intrusion front along the coastline.

* Corresponding author.
E-mail address: karatzas@mred.tuc.gr (G.P. Karatzas).

0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2007.05.027

Introduction

Optimization methods have been used in most areas of engineering, business, and sciences for decision-making problems. In recent years, various environmental problems such as the policy planning management of solid wastes, the optimal design of a water distribution network, and the design of groundwater remediation systems have been addressed combining numerical simulation models with mathematical and/or heuristic methodologies (Linton et al., 2002; Montesinos et al., 1999; Hilton and Culver, 2000). In the field of groundwater resources management previous works of Gorelick et al. (1984), Karatzas and Pinder (1993), Rogers et al. (1995), Rizzo and Dougherty (1996), Minsker and Shoemaker (1998), Aly and Peralta (1999), Papadopoulou et al., 2003, 2007 have obtained solutions of groundwater management problems with the application of linear, non-linear and heuristic optimization algorithms in combination with simulation models.

The development of optimal policies for the rational management of the subsurface water in coastal regions based on optimization methodologies has been occupied the scientific community for more than two decades due to the rapid water quality deterioration in these regions. Gorelick et al. (1984) were among the firsts that combined a non-linear groundwater model (SUTRA) that considered the influence of the variable density between fresh and saline water with a non-linear optimization method (MINOS) to formulate and solve a management model that can consider linear and non-linear objective functions subject to linear and non-linear constraints. The solution to the non-linearly constrained problem was obtained by solving a sequence of linearly-constrained sub-problems, however only a local optimal solution could be guaranteed. Willis and Finney (1988) presented a planning model for the control of seawater intrusion in a coastal aquifer in Taiwan using quadratic programming combined with the influence-coefficient method and the reduced-gradient method in conjunction with a quasi-Newton algorithm. Their results showed that the multi-objective optimization problem has a flat response surface, thus different well patterns give very nearly the same value of the objective function. Finney et al. (1992) developed an optimization model to control seawater intrusion in a multiple-aquifer system in Indonesia by minimizing the total squared volume of intruded seawater. Their results showed that a redistribution of pumping and recharge wells could change the spreading of seawater intrusion drastically. Gordon et al. (2000) presented a non-linear non-smooth optimization model of a regional aquifer under salinization conditions. The non-linear constraints were incorporated in the objective function transforming it into a non-smooth function. A sub-gradient method was used that locates a ''bundle'' of the sub-gradients which actually defines the possible directions and chooses the best to improve the objective function. Cheng et al. (2000) combined a sharp-interface saltwater-intrusion model with a Genetic Algorithm (GA) in order to maximize the extracted freshwater volume without causing the invasion of saltwater into the wells. The imposed constraints were added in the objective function as penalty terms and the GA was used to solve the new unconstrained problem. The multiplicity of the solutions as the number of the candidate wells increases using a GA was addressed in their example problem. Cai et al. (2001) combined a GA with linear programming (LP) to solve large non-linear management problems by identifying and fixing a set of complicating model variables. The GA was used to vary the complicating variables and the LP algorithm was used to compute the optimal objective value for each set of the fixed values suggested by the GA. The results showed convergence to local solutions. Mantoglou (2003) developed a seawater intrusion model where the constraints are expressed as analytical functions in the optimization methodology to obtain the optimal pumping strategy. A linear and a non-linear formulation were presented that were solved using the Simplex Method and sequential quadratic programming, respectively. The optimal solution was very sensitive to aquifer's heterogeneities and recharge rates.

In this paper, the optimal management of fresh water resources in coastal regions based on environmental criteria is considered. The study focuses on the determination of an optimal pumping scheme that will ensure adequacy of portable water demand in coastal regions without deteriorating the quality of the fresh water due to the seawater intrusion. The problem is formulated as the maximization of the total extracted fresh water volume from the pumping wells subject to a set of constraints related to the lower acceptable fresh water hydraulic heads in specific positions that have to be satisfied in order to meet the imposed environmental criteria of the region.

Initially, the Simplex method is used to solve the constrained optimization problem; a piecewise linearization of the non-linear optimization problem is obtained by sequential implementation of the Simplex algorithm. Additionally, the solution of the non-linear optimization problem is obtained using a Differential Evolution (DE) algorithm. DE has been demonstrated to be one of the most promising novel Evolution Algorithms (EAs), in terms of efficiency, effectiveness and robustness. Similarly to the rest of EAs, no information concerning the gradients of the objective function is needed in order to guide the optimization procedure. In the implementation presented in this paper, the constraints are combined with the objective function as penalty terms, to form a fitness function which is minimized using the DE algorithm. A comparison of the results obtained by the two different optimization approaches is performed and a sensitivity analysis is employed in order to examine the influence of the active pumping wells in the evolution of the seawater intrusion front along the coastline.

Deterioration of water quality in coastal regions

The multiple uses of the coastal water resources and the necessity of maintaining them in good quality require rational design and management. The water quality deterioration due to seawater intrusion that is observed in the coastal aquifers, especially during the summer season, is considered as the main environmental problem for these regions and it is directly related to seawater intrusion phenomenon and its development. The sensible balance between fresh and saline water in coastal aquifers is dynamic and the