Journal of Hydrology 478 (2013) 63–76

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

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

A groundwater management tool for solving the pumping cost minimization problem for the Tahtali watershed (Izmir-Turkey) using hybrid HS-Solver optimization algorithm

M. Tamer Ayvaz [a,*], Alper Elçi [b]

[a] Department of Civil Engineering, Pamukkale University, TR-20070 Denizli, Turkey
[b] Department of Environmental Engineering, Dokuz Eylul University, TR-35160 Buca-Izmir, Turkey

ARTICLE INFO

Article history:
Received 24 August 2012
Received in revised form 12 November 2012
Accepted 20 November 2012
Available online 29 November 2012
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Aldo Fiori, Associate Editor

Keywords:
Groundwater management
Pumping cost minimization
Simulation–optimization
HS-Solver

SUMMARY

This study proposes a linked simulation–optimization model to solve the groundwater pumping cost minimization problem for existing and new wells to satisfy any given water demand. The proposed model integrates MODFLOW-2000 with HS-Solver which is a recently proposed global–local hybrid optimization algorithm that integrates heuristic harmony search (HS) algorithm with the spreadsheet Solver add-in. Using the proposed model, a pumping cost minimization problem is solved for different number of wells by considering the pumping rates as well as the locations of additional new wells as the decision variables. Some physical and managerial constraints are defined for this problem. These constraints that need to be satisfied in the optimization process are set up using the penalty function approach. The performance of the proposed model is evaluated on the groundwater flow model of the Tahtalı watershed (Izmir-Turkey), an urban watershed which is a key component of Izmir's water supply system. Also, a sensitivity analysis is performed to evaluate the model results for different sets of HS solution parameters. Results indicate that the proposed simulation–optimization model is found to be efficient in identifying the optimal numbers, locations, and pumping rates of the pumping wells for satisfying the given constraints. Results also show that the model is not only capable of obtaining just any mathematically plausible solution but a realistic one that can be confirmed by repetitive runs of the model.

1. Introduction

Managing groundwater systems is a challenging task since the quality and quantity of groundwater resources are continuously deteriorating mostly due to anthropogenic factors. Linked simulation–optimization models are essential tools in the development of management strategies for groundwater systems. The main idea of these tools is to evaluate modeling results and select the best management strategy using optimization models with respect to prescribed physical or managerial constraints (Singh and Datta, 2006).

Many studies in the literature deal with the solution of groundwater management problems through simulation–optimization models. These studies differ among themselves in the way governing PDEs are solved in the simulation stage and the types of algorithms used in the optimization stage (Ahlfeld et al., 2005). A detailed literature survey of groundwater management models and an overview of the applications can be found in Gorelick (1983), Willis and Yeh (1987), and Das and Datta (2001). Although the groundwater management studies have some differences in terms of the simulation models, the main differences stem from the variety of the optimization models. Initial studies about linked simulation–optimization based groundwater management were usually performed using gradient-based optimization methods. These methods include linear programming (LP) (Willis, 1983; Hallaji and Yazicigil, 1996; Mantoglou, 2003), nonlinear programming (NLP) (Gorelick et al., 1984; Finney et al., 1992), and dynamic programming (DP) (Jones et al., 1987; Culver and Shoemaker, 1992). Although these methods are efficient in finding optimum solutions with reasonable computational times, their accuracy is mostly tied to the initial solutions since groundwater management problems usually have non-convex solution spaces and hence obtaining the global optimum is not guaranteed at all times (McKinney and Lin, 1994; Ayvaz, 2009). Therefore, heuristic optimization algorithms are generally preferred for the solution of groundwater management problems through simulation–optimization models. Many heuristic optimization algorithms mimic some natural phenomena. These include natural selection and evolution in genetic algorithm (GA) (Holland, 1975; Goldberg, 1989), physical annealing process in simulated annealing (SA) (Kirkpatrick et al., 1983), social behaviors of birds or fishes in

* Corresponding author. Tel.: +90 258 296 3384; fax: +90 258 296 3460.
E-mail addresses: tayvaz@pamukkale.edu.tr (M.T. Ayvaz), alper.elci@deu.edu.tr (A. Elçi).

0022-1694/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2012.11.045

particle swarm optimization (PSO) (Kennedy and Eberhart, 1995), finding shortest paths between nest and a food source in ant colony optimization (ACO) (Dorigo et al., 1996), and musical improvisation process in harmony search (HS) (Geem et al., 2001).

Many studies that apply heuristic optimization methods to the solution of groundwater management problems are published in the literature. One of the first applications was done by McKinney and Lin (1994) in which three separate management problems were solved including maximization of total pumping and minimization of pumping cost to satisfy the given water demand, and minimization of the remediation cost. McKinney and Lin (1994) performed a detailed analysis on solving these three problems and showed the superiority of GA by solving the same problems with LP and NLP. In a later study, Wang and Zheng (1998) compared the performance of GA and SA by solving the same management problems of McKinney and Lin (1994). Their results showed that both GA and SA give nearly identical or better solutions than those obtained by several traditional solution methods. Wu et al. (1999) developed a solution approach called GA based SA penalty function approach (GASAPF) to solve groundwater management problems. Their results showed that GASAPF model can be effective in solving these problems. Zhu et al. (2006) developed a groundwater management model which uses the shuffled complex evolution (SCE) algorithm in the optimization model. They applied their SCE based solution model to the solution of the management problems of the Yangtze Delta and compared their identification results with GA. Their results indicated that SCE based optimization model provides better results than GA for the same flow conditions. Ayvaz (2009) developed a combined simulation–optimization model where MODFLOW (Harbaugh, 2000) was used as the simulation model and HS as the optimization model. Ayvaz (2009) solved the same problem of McKinney and Lin (1994) with this model and obtained identical or better results than those obtained by GA. Sedki and Ouazar (2011) compared the performance of two common swarm intelligence techniques namely PSO and ACO for the solution of several groundwater management problems. Their results indicated that while the convergence speed and solution quality of PSO is better than ACO for the problems with small number of decision variables, ACO provides better results for the solutions with high number of decision variables.

It should be noted that all these examples considered fixed locations of pumping wells such that the coordinates of wells remain constant during the search process. Although fixed well based solution approaches are successful in determining the optimum pumping schedule for existing wells, they are not suitable to find potential locations of new wells to satisfy the given groundwater demand. Therefore, pumping well locations as additional decision variables must be considered together with associated pumping rates. In the current literature, studies that consider variable well locations to solve groundwater management problems through heuristic approaches are limited. Huang and Mayer (1997) developed a GA based solution model that considers the well locations as discrete decision variables for solving remediation system design problems. Park and Aral (2004) developed a multi-objective optimization model which is based on the progressive GA (PGA). They determined pumping rates and corresponding well locations in coastal aquifers. Ayvaz and Karahan (2008) developed a GA based solution approach to determine the number, locations and pumping rates of illegally drilled pumping wells. Similarly, Lin and Yeh (2008) developed a SA based solution model to determine the pumping source information including source locations, pumping rates, and pumping periods. Gaur et al. (2011a) developed a groundwater management model to determine the locations and pumping rates of potential wells by integrating the analytical elements method (AEM) to a PSO based optimization model. Similarly, Gaur et al. (2011b) compared the performance of two management models which were developed by combining AEM with PSO (AEM-PSO) and finite difference solution of governing PDEs with PSO (FDM-PSO). It should be noted that although heuristic optimization approaches were successively employed to solve several management problems, they may require long computation times to precisely find the optimum solution and satisfy the given physical and managerial constraints (Ayvaz et al., 2009).

Recently, hybrid optimization algorithms were successfully used for the solution of complex optimization problems with a non-convex solution space. These algorithms integrate heuristic and gradient-based algorithms such that the main objective is to utilize the global exploring capability of heuristic and strong fine-tuning property of gradient-based algorithms. In this integration, the global search process starts with multiple starting points and explores the entire search space, and then, gradient-based search methods find the optimum solution by assigning the results of global search as their initial values (Ayvaz et al., 2009). Although hybrid optimization algorithms can be effective in finding the global optimum precisely, programming of them is usually difficult since most of the gradient-based algorithms require some advanced mathematical calculations such as partial derivatives, Jacobian/Hessian matrices, and inversions (Ayvaz et al., 2009). Therefore, developing a robust hybrid algorithm can be a challenging task.

Nowadays, spreadsheet programs have become an essential tool for performing engineering calculations due to their popularity and availability. Most commercial spreadsheet packages contain a "Solver" add-in to solve optimization problems (Frontline Systems, 2012). The main advantage of "Solver" is that it does not only effectively solve many linear, nonlinear, and mixed-integer type optimization problems, but also successfully satisfies the given constraints. In addition, it is easy to use since it does not require much knowledge about programming gradient-based optimization algorithms.

Recently, a new hybrid optimization algorithm, HS-Solver, is proposed by (Ayvaz et al., 2009). HS-Solver consists of the integration of heuristic HS optimization algorithm with the spreadsheet Solver add-in. In this integration, a set of multiple solutions are generated using HS based on its computational structure, and then, the generated solutions are improved by the Solver. This type of solution sequence makes finding the global optimum solution easier than both global and local searches by HS and Solver, respectively. Ayvaz and Elçi (2013) recently applied HS-Solver for the solution of two groundwater management applications. Their first application deals with the solution of groundwater pumping maximization problem on a hypothetical aquifer model with fixed well locations. They applied HS-Solver to the solution of the related problem and compared their identification results with those obtained by different solution approaches (McKinney and Lin, 1994; Wang and Zheng, 1998; Wu et al., 1999; Ayvaz, 2009). In their second application, they applied HS-Solver to the solution of pumping maximization problem for the groundwater flow model of the Tahtalı watershed (Izmir-Turkey). They considered 17 pumping wells with fixed locations and maximized their pumping rates using both HS and HS-Solver. The results of both of their applications indicate that HS-Solver does not only provide better results than other deterministic and heuristic based solution approaches, but also solves the pumping maximization problems with much lower iteration numbers.

The main objective of the present study is to propose a new groundwater management model for existing and new wells that solves the pumping cost minimization problem by satisfying any given water demand. In the proposed model, the groundwater flow process is simulated using MODFLOW-2000 (Harbaugh, 2000), a modular three-dimensional finite difference groundwater flow model. This MODFLOW based simulation model is then integrated