Journal of Hydrology 511 (2014) 736–749

Contents lists available at ScienceDirect

Journal of Hydrology

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

Differential-Evolution algorithm based optimization for the site selection of groundwater production wells with the consideration of the vulnerability concept

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ARTICLE INFO

Article history:
Received 2 August 2013
Received in revised form 13 December 2013
Accepted 30 January 2014
Available online 14 February 2014
This manuscript was handled by Corrado Corradini, Editor-in-Chief

Keywords:
Optimization
Groundwater vulnerability
Pumping maximization
Cost minimization
MODFLOW
Izmir

SUMMARY

The objective of this study is to present an optimization approach to determine locations of new groundwater production wells, where groundwater is relatively less susceptible to groundwater contamination (i.e. more likely to obtain clean groundwater), the pumping rate is maximum or the cost of well installation and operation is minimum for a prescribed set of constraints. The approach also finds locations that are in suitable areas for new groundwater exploration with respect to land use. A regional-scale groundwater flow model is coupled with a hybrid optimization model that uses the Differential Evolution (DE) algorithm and the Broyden–Fletcher–Goldfarb–Shanno (BFGS) method as the global and local optimizers, respectively. Several constraints such as the depth to the water table, total well length and the restriction of seawater intrusion are considered in the optimization process. The optimization problem can be formulated either as the maximization of the pumping rate or as the minimization of total costs of well installation and pumping operation from existing and new wells. Pumping rates of existing wells that are prone to seawater intrusion are optimized to prevent groundwater flux from the shoreline towards these wells. The proposed simulation–optimization model is demonstrated on an existing groundwater flow model for the Tahtalı watershed in Izmir–Turkey. The model identifies for the demonstration study locations and pumping rates for up to four new wells and one new well in the cost minimization and maximization problem, respectively. All new well locations in the optimized solution coincide with areas of relatively low groundwater vulnerability. Considering all solutions of the demonstration study, groundwater vulnerability indices for new well locations range from 29.64 to 40.48 (on a scale of 0–100, where 100 indicates high vulnerability). All identified wells are located relatively close to each other. This implies that the method pinpoints the best area for new wells both in terms of groundwater quantity and quality. Furthermore, sensitivity analysis results indicate that identification results are insensitive to the selection of DE parameters.

1. Introduction

One of the important tasks in managing groundwater resources is to find locations for new production wells that provide sufficient amount of water in a sustainable and environmentally safe manner. Site selection of wells can be formulated as an optimization problem that can be solved using simulation–optimization models. There are many studies that apply heuristic optimization methods to the solution of groundwater management problems (e.g. Ayvaz, 2009; McKinney and Lin, 1994; Wu et al., 1999). However, these studies apply 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 optimum pumping for existing wells, they may not be suitable to find potential locations of new wells to satisfy the given demand. Therefore, pumping well locations as decision variables must be considered together with associated pumping rates to develop sustainable groundwater management strategies. In the current literature, studies that consider variable well locations to solve groundwater management problems through heuristic approaches are limited (e.g. Ayvaz and Elçi, 2013; Ayvaz and Karahan, 2008; Gaur et al., 2011; Huang and Mayer, 1997; Park and Aral, 2004).

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http://dx.doi.org/10.1016/j.jhydrol.2014.01.071
0022-1694/

Ideally, groundwater production wells should be drilled in aquifers that are less prone to contamination. There are many factors that determine the vulnerability of an aquifer to contamination by point and non-point sources. While the location of the source of groundwater contamination may be above or under the land surface, the concept of vulnerability typically relates to anthropogenic contaminants released above the water table at or near the land surface. Therefore, groundwater vulnerability is commonly regarded as a dimensionless and an intrinsic property of the aquifer that defines the likelihood of breakthrough of any contaminant released at the land surface. Mapping of vulnerability is a well-known procedure and a variety of methods have been developed to assess and map groundwater vulnerability. Overviews of these methods can be found in Gogu and Dassargues (2000) and Elçi (2012). The concept of groundwater vulnerability mapping can be considered as a viable tool in groundwater management. It has been used in the optimization of groundwater monitoring networks (Baalousha, 2010; Preziosi et al., 2013), and in the prioritization of groundwater wells that need to be protected from contamination (Exposito et al., 2010).

The objective of this study is to develop a simulation–optimization approach to determine the optimum location of groundwater production wells. Several factors like the intrinsic vulnerability of the aquifer to contamination, the prevention of seawater intrusion and cost of well installation and pumping are considered in the well site selection process. Here, two different management problems are formulated: the objective of the first problem is to maximize the pumped groundwater from new wells that are added to already existing wells; and the second problem aims to minimize the well installation and operation costs while meeting the given groundwater demand. Pumping rates of existing wells that are prone to seawater intrusion are optimized to prevent groundwater flux from the shoreline towards these wells. Also, the purpose of the optimization is to find new well locations that are relatively less susceptible to groundwater contamination and are in suitable areas for new groundwater exploration with respect to land use.

An original aspect of the presented approach is that intrinsic aquifer vulnerability is considered in the optimal well site selection process. This is implemented by using a previously calculated groundwater vulnerability index distribution as criteria with the aim to prefer less vulnerable aquifers to contamination as the source for groundwater. Some physical and operational constraints are considered by the simulation–optimization procedure such that hydraulic head values at selected well locations must not be lower than the bottom elevation at that point, locations of the selected wells must not be in any inactive grid cells within the finite difference model domain, depth of the proposed wells must not exceed a permissible limit, and saltwater intrusion problem along the coast line must not occur due to excessive pumping. All of these constraints are included in the optimization model in the form of penalty functions.

2. Method development

The optimum location of new groundwater pumping wells is determined by coupling a regional-scale groundwater flow model with an optimization process. During this process, viable solution sets of well locations and associated pumping rates are generated as input for the execution of the simulation process. In the simulation process, the hydraulic head distribution in the aquifer is determined using a groundwater flow model. The methodology for the site selection of new pumping wells is demonstrated using a groundwater modeling case study of the Tahtalı watershed in Izmir, Turkey (Elçi et al., 2010). The presentation of the coupled simulation–optimization method and the integration of the groundwater vulnerability concept and land use information with the optimization procedure are provided in the following sections.

2.1. Simulation model

The principal part of the presented approach is the simulation model since it calculates the hydraulic head field over the flow domain considering the location and pumping rate of each production well. The simulation model solves the governing equation for two dimensional groundwater flow in an unconfined aquifer system that can be given as follows:

$$\nabla \cdot [\mathbf{K} h \nabla h] = W - R \tag{1}$$

where ∇ is the two dimensional gradient operator, $\mathbf{K}$ is the hydraulic conductivity, h is the hydraulic head, W is the sink/source term, and R is the areal groundwater recharge rate. Eq. (1) can be solved with any solution approach including finite-differences, finite-element or analytical elements methods. MODFLOW-2000 is used in this study for simulating the groundwater flow process rather than directly solving Eq. (1) using these methods.

2.2. Optimization model: hybrid Differential Evolution algorithm

The solution of the well site selection optimization problem is primarily obtained by the hybridized version of the Differential Evolution (DE) algorithm. DE (Storn and Price, 1997) is a heuristic optimization method which has similar characteristics as genetic algorithms (GA) in terms of operation and calculation schemes. DE can be used to solve optimization problems for non-differentiable, non-continuous or noisy solution spaces and can handle continuous, discrete and integer variables or multiple constraints. As in GA, information concerning the gradients of the objective function is not needed to guide the optimization procedure. The key difference of DE and GA is that DE can solve an optimization problem using real coded decision variables rather than the binary strings as in GA. The mutation, crossover, and selection operators of GA are also used in DE in a similar manner. However, unlike GA, all the candidate solutions in DE are subjected to evolution and the evolved solutions are directly transferred to next generations, if the objective function values are improved. It is shown that global optimum or near global optimum solutions can be effectively obtained by DE. Mathematically, an optimization problem can be solved using DE as follows:

Let p be the number of populations (i.e. number of candidate solutions), n be the number of decision variables of the optimization problem, G be the generation index, $\mathbf{x}_{i,G} = [x^j_{i,G}]|^p_{i=1}|^n_{j=1}$ be the vector which includes the values of decision variables to be determined, $\mathbf{x}_{\min} = \{x^j_{\min}\}|^n_{j=1}$ and $\mathbf{x}_{\max} = \{x^j_{\max}\}|^n_{j=1}$ be the vectors which include the lower and upper bounds of the decision variables, respectively. Using these definitions, the initial value of the jth decision variable in the ith candidate solution at the generation $G = 0$ can be generated as follows:

$$x^j_{i,0} = x^j_{\min} + r(0,1) \times (x^j_{\max} - x^j_{\min}) \tag{2}$$

where $r(0,1)$ represents a uniform random number within the range of $(0,1)$. After performing the initialization process, a new mutant vector of $\mathbf{v}_{i,G} = [v^j_{i,G}]|^p_{i=1}|^n_{j=1}$ is generated with respect to the vector of $\mathbf{x}_{i,G}$ using the mutation operator. Note that several mutation strategies are available to generate the new mutant vector. One of the most widely used is the "DE/rand/1" strategy, where the individuals of the mutant vector are chosen randomly, and one pair of solution is selected. The mutation strategy of DE/rand/1 can be defined as follows:

$$\mathbf{v}_{i,G} = \mathbf{x}_{r^i_1,G} + F\left(\mathbf{x}_{r^i_2,G} - \mathbf{x}_{r^i_3,G}\right) \tag{3}$$