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Optimization of the exploitation system of a low enthalpy geothermal aquifer with zones of different transmissivities and temperatures

K. Tselepidou, K.L. Katsifarakis*

Division of Hydraulics and Environmental Engineering, Department of Civil Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece

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A B S T R A C T

Market penetration of renewable energy sources, such as geothermal energy, could be promoted even by small cost reductions, achieved through improved development design. This paper deals with optimization of the exploitation system of a low enthalpy geothermal aquifer, by means of the method of genetic algorithms, which has been successfully used in similar problems of groundwater resources management. With respect to water flow, the aquifer consists of two zones of different transmissivities, while from the thermal point of view it may bear any number of zones with different temperatures. The optimization process comprises the annual pumping cost of the required flow and the amortization cost of the pipe network, which carries the hot water from the wells to a central water tank, situated at the border of the geothermal field. Results show that application of the proposed methodology allows better planning of low enthalpy geothermal heating systems, which may be crucial in cases of marginal financial viability.

1. Introduction

Soft and renewable energy sources, offer, in medium and long term, the best, if not the sole, solution to the world's energy problem, for the following reasons: a) impact of their use on the environment is much smaller than that of conventional energy sources and b) nature provides them continuously. Still, we have to use them in a sustainable way. Regarding geothermal energy in particular, Earth will provide us with heat for the next million years at predictable rates [1], but sustainable management of geothermal resources is required to preserve both their temperature and the means of transporting their heat content to the ground surface, namely the water (or steam) capacity of geothermal aquifers.

It should also be mentioned that increased share of renewables in the energy market promotes global stability, since it reduces the dependence of energy consumers on big oil companies, remote oil and natural gas producers and the respective transport means (tankers or pipes) and routes. Moreover, renewable energy sources have no military applications.

This paper deals with low enthalpy geothermal resources. Much more abundant than the high enthalpy ones, and more evenly distributed around the Globe, they can provide heat for space heating and other direct uses, thus covering an important part of energy demand. Analysis of their financial performance is rather complex. A comprehensive report is offered by Lund et al. [2]. Their current contribution to the energy balance is probably underestimated, since very often their use is not adequately recorded, at least quantitatively. It is certain, though, that their share can be substantially increased in many areas of the world, including the energy importing part of Europe. Greece is one of the countries with large unexploited potential [3,4].

As the financial performance of geothermal energy applications is still in most cases marginal (when environmental cost is not taken into account), its optimization is very important. It may even decide whether an investment plan will be materialized. This paper deals with cost minimization of a geothermal district heating scheme. Two major cost components are taken into account: a) annual pumping (operation) cost and b) amortization of the construction cost of the pipe network, carrying hot water from the wells to a central water tank, at the border of the geothermal area.

2. The optimization tool

The optimization tool, used in this paper, is based on the method of genetic algorithms, which has been initially introduced by Holland [5]. The scientific literature on their theoretical background and their applications is already quite rich (e.g. [6–8]). In brief, genetic algorithms are essentially a mathematical imitation of the biological process of evolution of species. They start with a number

* Corresponding author. Tel.: +30 2310 995634; fax: +30 2310995674.
E-mail addresses: kleonik@civil.auth.gr (K. Tselepidou), klkats@civil.auth.gr (K.L. Katsifarakis).

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of random potential solutions of the problem in hand. These solutions, which are called chromosomes, constitute the population of the first generation. In binary genetic algorithms, each chromosome is a binary string, e.g. [01001110]. The number of its characters, which are called genes, is usually predetermined.

Then a fitness value is assigned to each chromosome of the first generation, by means of a pertinent evaluation function or process. This process depends entirely on the specific application of genetic algorithms and may include a flow simulation model. It may also include a penalty function, to reduce chromosome's fitness, if the respective solution violates any of the constraints of the problem.

When evaluation of every chromosome is completed, the next generation is produced, through application of certain operators, which imitate biological processes. The main genetic operators are: a) selection b) crossover and c) mutation. Many other operators have been also proposed and used.

Selection, which is used first, is a mathematical imitation of Darwin's principle of the survival of the fittest and leads to the formation of an "intermediate population". All chromosomes participate to the selection process, each with its own probability of survival, which results from its fitness, already determined during the evaluation process. Thus, comparatively better chromosomes have statistically more copies in the intermediate population, while some of the worst perish. The most common selection procedures are the biased roulette wheel and the tournament. Moreover, many selection codes, following the so-called elitist approach, preserve separately at least one copy of the best chromosome for the next generation.

When the intermediate population is formed, some of its members are randomly selected to undergo crossover, mutation (and probably some other operators), while the rest pass to the next generation unchanged. Crossover is a recombination process, namely an exchange of parts between pairs of chromosomes. The aim is to produce at least one improved new solution. Mutation on the other hand applies to the characters (genes), which form the chromosomes (the selected gene is changed from 0 to 1 or vice-versa). Thus it may extend the search to more areas of the solution space or it may lead to refinement of already good solutions.

The whole process, i.e. evaluation–selection–crossover–mutation-additional operators, is repeated for a predetermined number of generations (or until a termination criterion is met). It is anticipated that, at least in the last generation, a chromosome will prevail, which represents a sub-optimal (if not the global optimal) solution of the problem. Identification of a number of very good solutions is an additional asset of the method of genetic algorithms.

In the code used in this paper, selection is accomplished by means of the tournament method. Moreover, the elitist approach is followed. Then typical crossover and mutation are used, together with antimetathesis, an operator described by Katsifarakis et al. [9]. Fulfillment of constraints is guaranteed by means of a chromosome correction process.

3. Applications to geothermal aquifers

Pumping cost for a geothermal district heating scheme depends on the hydraulic and thermal features of the respective geothermal aquifer. Considering the latter as hydraulically and thermally homogeneous is plausible in certain cases, but it is usually an oversimplification. Seeking a better balance between simplicity and accuracy, we have considered a geothermal aquifer consisting of 2 zones of different transmissivities (T_1 and T_2) and 4 zones of different temperatures. Their boundaries, in all figures, are shown with black and white lines respectively, while the zone number of the latter is denoted by the corresponding temperature θ_1, θ_2, θ_3 and θ_4. A square area, with dimensions 3×3 km, is available for geothermal development, its borders also shown with white line. Moreover, we assume that temperatures are not influenced by pumping.

The total required flow rate Q_T depends on the average temperature of pumped water and varies from 500 to 600 l/s. To pump Q_T, 4 existing and 6 new wells will be used, shown in all figures with white and black circles respectively. The result of the optimization procedure will be the distribution of Q_T to the wells, together with the locations of the new ones. Then, each chromosome (namely each solution of the problem) is a combination of 10 well flow rates (each varying from 0 to 255 l/s, namely up to almost the half of Q_T) and 6 pairs of coordinates (each varying from 0 to 3000 m).

The chromosome evaluation function results from the 2 cost items that enter the optimization procedure, namely: a) the annual pumping cost and b) the amortization of the construction cost of the pipe network, carrying water from the wells to a central water tank, located at the boundary of the geothermal area and shown as a small square in all figures. Pumping cost can be expressed as:

$$K_\alpha = A_\alpha \sum_{i=1}^{N} H_i \cdot Q_i \tag{1}$$

where $N = 10$ is the number of the wells, H_i is the distance between the water level at well i and a predefined level, Q_i is the flow rate of well i (in l/s) and A_α a pumping cost coefficient, depending on the duration of the heating period, the electricity cost and the efficiency of the pumps. In all application examples A_α has been considered as constant and equal to 2.7, as in [10] and [11]. Considering that the difference between the aforementioned predefined level and the initial undisturbed hydraulic head level in the aquifer is constant, K_α varies exactly as $K1_\alpha$, which is given as:

$$K1_\alpha = A_\alpha \sum_{i=1}^{N} s_i \cdot Q_i \tag{2}$$

where s_i is the hydraulic head level drawdown at the perimeter of well i, measured from the initial horizontal undisturbed level. To calculate $K1_\alpha$, one has to calculate all s_i. Hydraulic head level drawdown s at any point (x, y) of an "infinite" aquifer, bearing 2 zones of different transmissivities, due to pumping of one well, depends on the zone, to which that point and the well belong. If both of them are located in zone 1, equation (3) holds, while if the well is in zone 1 and the point in zone 2, equation (4) should be used.

$$s = \frac{Q_w}{4\pi T_1} \ln \frac{R^2}{(x-x_w)^2+(y-y_w)^2} + \frac{C_1 Q_w}{4\pi T_1} \ln \frac{R^2}{(x+x_w)^2+(y-y_w)^2} \tag{3}$$

$$s = \frac{C_2 Q_w}{4\pi T_1} \ln \frac{R^2}{(x-x_w)^2+(y-y_w)^2} \tag{4}$$

In Eqs. (3) and (4), which result from the method of images [12], Q_w is the well flow rate, x_w, y_w its coordinates and R its radius of influence, with the y axis of the coordinate system coinciding with the interface of the two zones. Finally T_1 is the transmissivity of zone 1, while constants C_1 and C_2 are given as:

$$C_1 = \frac{1-\gamma}{1+\gamma} \tag{5}$$

$$C_2 = \frac{2\gamma}{1+\gamma} \tag{6}$$