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Optimal management of a theoretical coastal aquifer with combined pollution and salinization problems, using genetic algorithms

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ABSTRACT

The paper discusses optimal management of a theoretical coastal aquifer, providing water for drinking and/or irrigation purposes, which is threatened by seawater intrusion from the coast and by non-conservative pollutant plumes from the inland. A new computational tool, able to address the combined pollution-salinization problem, is used. It optimizes the classic Pump-And-Treat and Hydraulic Control techniques without compromising aquifer's sustainability. Optimization entails minimization of pumping, pipe network construction and pumped polluted water's remediation costs. Practically, the goal is: find the best distribution of total required flow rate to existing wells and the best locations and flowrates of additional abstraction wells, in order to protect the aquifer with minimal management costs. The respective objective function includes a complex penalty function. The optimization technique used is a binary genetic algorithm including elitism. In order to maintain a reasonable balance between computational volume and accuracy, a simplified equivalent 2D groundwater flow field is simulated by a boundary element method, while advective mass transport (pollution spread and seawater intrusion) is simulated by a particle tracking code.

1. Introduction

Water and energy are closely interrelated, both at the planet scale and at the scale of human works. At the planet scale, the hydrologic cycle, which produces renewable fresh water resources, is fueled by the energy of the Sun. Water, on the other hand, due to the energy that it carries, changes the shape of the Earth, either abruptly, as during flood events, or imperceptibly, during long periods of time.

The relationship between water and energy resources is quite close at the scale of human works, too. Quite often we correlate them in a negative way, focusing on water pollution and consumption due to energy production, use and transport (e.g. Ref. [1]). This is part of the whole picture, though. For each water drop that reaches our homes, energy has been used at different stages, e.g. to pump ground water, to treat it, to render it potable and to transport it to our houses, through water supply networks (e.g. Ref. [2]). No water deficit problem would exist, if we had an abundant, cheap and safe energy source for sea water desalination. Moreover, energy (together with chemicals) is required to run sewer treatment plants.

Quite often, problems of optimal water resources management are mainly energy management problems. This is particularly true with optimal management of aquifers, which are threatened by natural or anthropogenic pollution sources, such as industrial activity, energy production, intensive agriculture including systematic use of fertilizers and pesticides, oil leakage or leakage from legal or illegal landfills, etc.

Optimal management of polluted aquifers requires complex pollution control or remediation techniques [3], which include installation and operation of a well network, in order either to control the spread of a contaminant via manipulation of groundwater levels and flow directions (Hydraulic Control-HC) or to reduce the contaminant mass, pumping it partially or thoroughly, in order to meet a target concentration or global mass fraction and even treat it accordingly (Pump and Treat-PAT) [4].

Depending on the way the pollution plumes are captured or contained [5], contaminant control methods can also be classified as a) concentration control (maximum concentration levels compliance at control points) [6], b) hydraulic control (predefined head difference, gradient, or velocity constraints at specific points) [7], and c) advective control [8]. Practically, the aforementioned

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techniques, as implemented here, are different versions of the advective control approach, specifically the Particle Tracking Method (PTM), where hydrodynamic dispersion is neglected [9–12]).

The ultimate goal of the ongoing research is optimal management of polluted aquifers, with minimum total solution cost, without compromising aquifer's further sustainability. In all cases, energy is the main cost item. From the computational point of view, the target is to decide the number of new wells and their coordinates, together with the new and existing wells' flowrates. The optimization process can vary from simple series of tests or trial and error procedures [13], to linear [14] or non-linear programming [15,16], and even to heuristics or meta-heuristics and modern evolutionary algorithms [9–12,16–18]. The latter often require simplification of the flow field (equivalent 2D fields) due to the excessive computational load deriving from their iterative nature.

Coastal aquifers often face an additional form of water quality degradation: salinization due to the water table drawdown near the shoreline, resulting from excessive pumping. In such cases, re-planning of pumping schemes (flow rates or/and well locations) is required, in order to guarantee operational continuance, without salinization of pumping wells or further seawater intrusion.

The general class of all the above problems is that of constrained, nonlinear, stochastic, multi-objective optimization problems [3]. In that class, optimization of HC and PAT management strategies has been extensively studied in inland polluted aquifers and coastal aquifers under sea intrusion separately, but there is little research concerning the combined problem of optimal management of a coastal aquifer threatened by both pollution plumes from the inland and sea intrusion from the coastline. This paper presents a new software application "OptiManage" (Visual Basic), which deals with the combined problem of the optimal management of a coastal aquifer, threatened simultaneously by pollution plumes from the inland and sea intrusion from the coastline. When a given total fresh water flow rate is required from an existing pumping scheme, "OptiManage" can find the best flow rate distribution among the existing wells and decide on the suitable locations and flow rates of additional wells in order to protect the existing ones from pollution and all wells from pumping seawater (problem version A1) during the studied period of time (i.e. non-conservative pollutant's deactivation period), with minimum management costs. Alternatively, salinization prevention can refer to the aquifer in general and not only to the wells. In this case, an inflow check in the coastline boundary elements is used (problem version A2 [12]).

2. Flow field simulation (BEM) and mass transport (PTM)

The use of genetic algorithms as the optimization tool dictates simplification of the hydraulic model in order to reduce the vast computational load. Hence, an equivalent 2D flow field is studied and a simplified advective PTM is used to simulate advective pollutant transport only [19], while the flow field is simulated using the BEM [12,20].

BEM is based on Green's 2nd law. The hydraulic head h and velocity V at internal points of a flow field Ω are calculated from the values of h and q = ∂h/∂n along the boundary S of Ω. During numerical implementation, the boundary S is divided into N line segments (boundary elements), where h and q are assumed constant. Missing h and q values on the boundary elements are produced first, through solving a system of N equations and unknowns. Then h at any internal point of the field can be calculated as:

$$h_i = \frac{1}{2\pi}\cdot\left[\sum_{j=1}^{N}\frac{Q_w}{T}\ln\left(\frac{1}{r_{iw}}\right) + \sum_{j=1}^{N} h_j\cdot\int_{\Gamma_j}\frac{\bar{r}_{ij}\cdot\bar{n}}{r_{ij}^2}d\Gamma_j + \sum_{j=1}^{N}\frac{\partial h_j}{\partial n}\cdot\int_{\Gamma_j}\ln\left(\frac{1}{r_{iw}}\right)d\Gamma_j\right] \quad (1)$$

where, N is the number of boundary elements, Q_w is the flow rate of well W, r_{iw} and r_{ij} are distances shown in Fig. 1a. The line integrals have been analytically evaluated [21] and applied to various groundwater modelling studies [12,20,22].

In cases of aquifers with locally homogeneous zones of different transmissivities, two assumptions are made: a) in each zone k transmissivity T_k is constant and the Poisson equation applies and b) at every point along the two zones' interface, the compatibility and continuity equations apply [21,22]. The next step is calculation of the velocities at internal points within the different zones of the aquifer by means of Eqs. (2) and (3), in order to simulate advective transport of pollutant and seawater particles, as implemented before in similar problems [11,12,22].

$$V_x = \frac{K}{2\cdot\pi\cdot n}\cdot\sum_{w=1}^{W}\frac{Q_w\cdot c_w}{T\cdot r_{iw}^2} - \sum_{j=1}^{N} h_j\frac{l_1\cdot(l_2\cdot c_2\cdot\cos\alpha + l_3\cdot c_1\cdot\cos\beta}{(l_2\cdot l_3)^2\cdot\sin\gamma} - \sum_{j=1}^{N}\frac{\partial h_j}{\partial n}\cdot\left[\frac{\gamma\cdot c_2}{l_3\cdot\sin\alpha} + \frac{c_1 - c_2}{l_1}\cdot\left(\gamma\cdot\cot\alpha + \ln\frac{l_2}{l_3}\right)\right] \quad (2)$$

$$V_y = \frac{K}{2\cdot\pi\cdot n}\cdot\sum_{w=1}^{W}\frac{Q_w\cdot d_w}{T\cdot r_{iw}^2} - \sum_{j=1}^{N} h_j\frac{l_1\cdot(l_2\cdot d_2\cdot\cos\alpha + l_3\cdot d_1\cdot\cos\beta}{(l_2\cdot l_3)^2\cdot\sin\gamma} - \sum_{j=1}^{N}\frac{\partial h_j}{\partial n}\cdot\left[\frac{\gamma\cdot d_2}{l_3\cdot\sin\alpha} + \frac{d_1 - d_2}{l_1}\cdot\left(\gamma\cdot\cot\alpha + \ln\frac{l_2}{l_3}\right)\right] \quad (3)$$

where, $c_1 = x_j - x_i$, $d_1 = y_j - y_i$, $c_2 = x_j + 1 - x_i$, $d_2 = y_j + 1 - y_i$, $c_w = x_w - x_i$, $d_w = y_w - y_i$, while α, β, γ, l_1, l_2 and l_3 are shown in Fig. 1b.

The study period is discretized into equal timesteps. Particles of infinitesimal mass simulate pollutants or seawater. Their displacements during each timestep ΔT are calculated by local velocity components, which are assumed to be constant during each ΔT. In this way, the trajectory of each particle is calculated as a crooked line. The finer the discretization (larger number of ΔTs), the more realistic the trajectory is and the more it resembles a continuous curve.

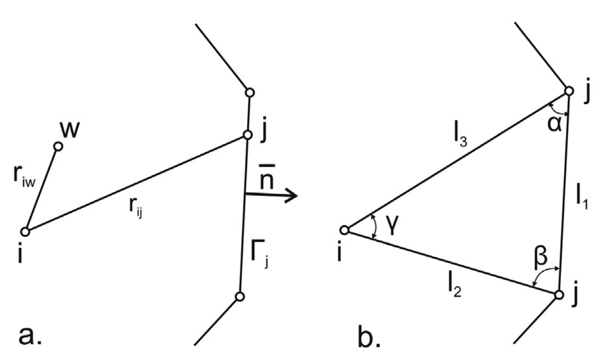

Fig. 1. Auxiliary figure related to the formulation of boundary elements.