Genetic Algorithms in Polluted Coastal Aquifers' Management

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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. It follows authors' previous work that dealt with the minimization of the aquifer's management cost, namely optimization of Pump-And-Treat and Hydraulic Control techniques in order to pump a given flow-rate of fresh water, without compromising the aquifer's sustainability. Optimization, in this paper, on the other hand, entails maximization of the fresh water pumping flow-rate, provided that no well is polluted and no seawater intrusion occurs (Water Supply problem). Practically, the goal is: find the flow rates of existing abstraction wells and the fittest locations and flow rates of additional wells, in order to pump the highest total fresh water flow-rate, without further sea intrusion. An established robust computational tool, "OptiManage", entirely created by the authors, able to address the combined pollution-salinization problem, is used. OptiManage uses a binary genetic algorithm including elitism and a complex penalty function. The need to balance between computational volume and accuracy dictates the simulation of the groundwater flow field through a simplified surrogate 2D field, using a boundary element method, while a particle tracking code simulates the advective mass transport (pollution spread and seawater intrusion).

Key-Words: - genetic algorithms, coastal aquifer, groundwater pollution, seawater intrusion, maximum water supply, boundary elements, particle tracking

1 Introduction

Fresh groundwater degradation, as far as both quantity and quality are concerned, is already a global given. Human induced pollution and over-exploitation of water resources are the main causes, resulting in advanced aquifer degradation phenomena, where existing fresh water pumping wells and irrigated crops are threatened. Such incidents often require complex pollution control or remediation techniques like Hydraulic Control (HC) and Pump And Treat (PAT) technologies [1].

Both techniques include installation and operation of a well network, which together with the appropriate management of the existing wells, will be able to control the spread of a contaminant via manipulation of groundwater levels and flow directions (HC) or 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 (PAT). PAT is effective and efficient only if the contaminant is highly water-soluble or miscible, and not strongly sorbed to soil surfaces [2].

Formulations of contaminant control methods, on the basis of the plumes' capture or containment techniques [3], can be characterized as: a) concentration control (maximum concentration levels compliance at control points, e.g. [2]), b) hydraulic control (predefined head difference, gradient, or velocity constraints at specific points, e.g. [4]), and c) advective control [5]. The aforementioned HC and PAT techniques are implemented here as different versions of the advective control approach, specifically the Particle Tracking Method (PTM), where hydrodynamic dispersion is neglected [6-10].

Optimal planning and implementation of the aforementioned techniques entail decision of the number of new wells and their coordinates and the additional and existing wells' flowrates (if applicable depending on the problem version). Ultimate goal is the optimal management of the polluted aquifer with minimum total solution cost or maximum fresh water supply (classic problem of Water Supply or WS), without compromising pumping scheme's or even aquifer's further viability/sustainability, during predefined time periods or perpetually. The optimization process can vary from a simple series of tests or a trial and error procedure [11], to linear [12] or non-linear programming [13,14], even heuristics or meta-heuristics and modern evolutionary algorithms [6-10,14-16].

The implementation of these optimization methods in previous research efforts required simplification of the flow field (equivalent 2D fields) due to the excessive computational load deriving from their iterative nature. These problems also lead many researchers to implement a Boundary Element Method (BEM) to simulate the internal and external flow field boundaries [9,10]. The general class of all the above problems is that of constrained, nonlinear, stochastic, multi-objective optimization problems (CNSMOP) [3].

2 Simulating Flow Field and Mass Transport

The use of Genetic Algorithms (GAs) as an optimization technique implies a vast computational load, so the hydraulic model needs to be simplified. Hence, a surrogate 2D flow field is studied, while a simplified advective Particle Tracking Method (PTM) is implemented in order to simulate advective pollutant transport only [7-10]. For the same reason, a Binary Element Method is used to simulate the simplified 2D flow field [9,10].

2.1 Flow Field Simulation – Boundary Element Method (BEM)

The BEM simulated flow field (Ω) entails calculation of the hydraulic head h and velocity V at internal points of Ω, given the values of h and q=∂h/∂n along the boundary S of Ω. Green's 2nd law is used in order for the Laplace equation to be assumed to apply in the entire field, except for a singular point, where its value tends to infinity. Separation of the singular point from the rest of the field is achieved by a circle of infinitesimal radius. The numerical implementation entails the division of the boundary S into N line segments (boundary elements), where h and q are assumed constant. The h and q values on the boundary elements that are missing, are produced first, with the solution of a system of N equations and unknown variables. Then, h at any internal point of the field can be calculated:

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

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 [17] and applied to various groundwater modelling studies [9,15,18].

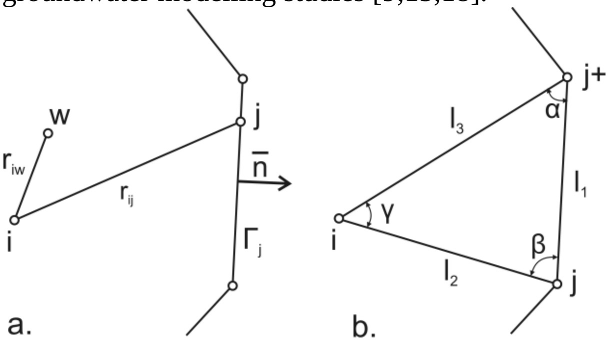

Fig. 1. Division of boundaries into boundary elements and relevant notations.

In order to include cases of locally homogeneous zones of different transmissivities, two assumptions apply: a) inside each zone k, transmissivity T_k remains constant and the Poisson equation applies, and b) at each point along the interface of two adjacent zones, the compatibility and continuity equations apply [17,19].

2.2 Mass Transport Simulation – Advective Particle Tracking Method (PTM)

The velocity field in any internal point within the different zones of the aquifer is calculated, as shown in Eq. 2 and 3, thus, advective transport of pollutant and seawater particles is simulated in the same fashion as in previous implementations for similar problems [6-8,10].

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

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

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 time-period is discretized into equal timesteps ΔTs. Pollutants and seawater are simulated by particles of infinitesimal mass, while local velocity components, assumed to be constant during each ΔT, are used to calculate the particles' displacements during each ΔT. Thus, each particle's trajectory is calculated as a crooked line, with finer discretization (larger number of ΔTs) producing more realistic trajectories resembling continuous curves.

A previous paper [10] by the authors analytically describes the methods and techniques used in order to apply a simple but effective mathematical simulation of the pollution plumes, the plumes' and seawater spread and the wells' pollution criteria. The internal and external boundaries of the field are here discretized into only 50 boundary elements (Fig. 2), in rather poor fashion, in order to test the limits of the boundaries' accuracy (ideally the discretization should be at least 5 times finer.

2.3 Theoretical Aquifer's Characteristics

The theoretical coastal aquifer is assumed to be confined and isotropic, with thickness b=50m, hydraulic conductivity $K=10^{-4}$ m/s and porosity n=0.2. The flow is assumed to be plane, horizontal, single-phase and steady. The aquifer includes three discrete homogeneous zones of different transmissivities (Fig. 2). The aquifer's southern boundary of constant hydraulic head (h=0 m) is actually the coastline (Dirichlet boundary condition). The northern boundary is also a constant head boundary (h=50 m), while the western and eastern boundaries are impermeable ($q=\partial h/\partial n=0$, Neumann condition), where n stands for the direction vertical to the boundary.

BEM exhibits intrinsically reduced accuracy near the boundary elements (distance < half the element's length), thus new wells can be placed only in specified permitted zones securely distanced from boundaries (here equal to a boundary elements' length, see Fig. 2).

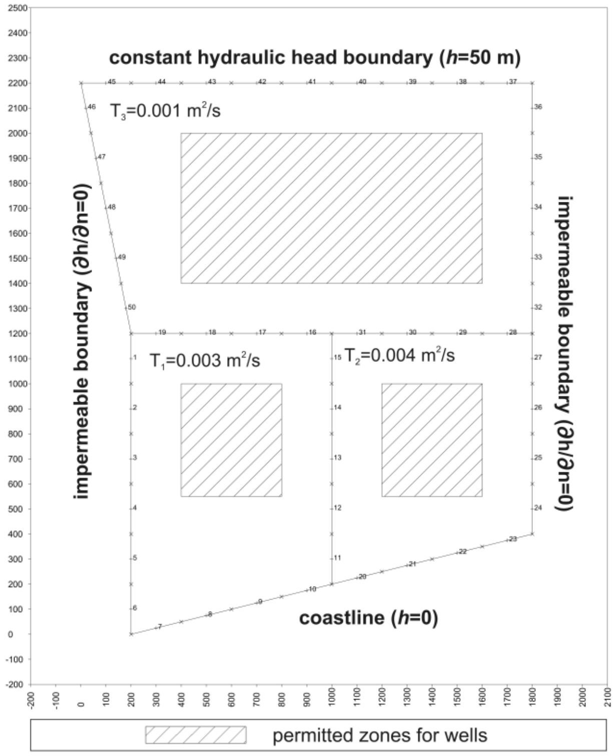

Fig. 2. 2D theoretical coastal aquifer indicating the permitted zones for installation of new wells.

3 Optimization Scenarios

The optimization of HC, PAT and WS management strategies has been studied extensively in inland polluted aquifers and coastal aquifers under sea intrusion separately, but there is little research concerning the combined problem of the optimal management of a coastal aquifer threatened by both pollution plumes from the inland and sea intrusion from the coastline. This paper presents the authors' own software application 'OptiManage', which can provide optimal solutions for that complex problem, optimizing a polluted coastal aquifer's management in any of the problem versions presented in Table 1.

Table 1. Versions of the optimization problems "OptiManage" can produce optimal solutions for.

Condition	**Problem version**				
	A1	**A2**	**B1a**	**B1b**	**B2b**
FV=Min	V	V	X	X	X
FV=Max	X	X	V	V	V
Salinization	PTM	Inflow	PTM	PTM	Inflow
Ex. Wells	V	V	V	X	X
Add. Wells	V	V	V	V	V

3.1 Management Cost Minimization (optimal HC or PAT implementation)

In case of a required total fresh water flow rate from existing pumping wells, 'OptiManage' can find the best distribution among the existing wells and decide on the suitable locations and flow rates of additional wells in order to minimize total management cost FV (pumping cost VB1 + pipe network costs VB2 + pumped polluted water's treatment cost VB3). The proposed pumping schemes must not entail pollution of the existing wells or salinization of any well (version A1) during the studied period of time (i.e. conservative pollutant's deactivation period). Alternatively, salinization prevention can refer to the aquifer in general and not only the wells, thus changing the salinization criterion from a particle tracking based method to an inflow check in the coastline boundary elements (version A2). OptiManage was successfully tested in this case in a theoretical polluted coastal aquifer in previous papers of the authors [10].

3.2 Fresh Water Pumping Maximization (optimal WS implementation)

In case of an attempt to fully exploit the coastal aquifer's groundwater resources, as described in this paper, 'OptiManage' can also find the optimal flow rates of the existing wells and best locations and flow rates of additional wells in order to maximize fresh water supply (B1a). Similarly to case 'a' there can be an alternative salinization criterion based to the inflow check (B2b), while for both the latter versions there are variations in case the use of the existing pumping scheme is non-binding (B1b and B2b, respectively).

The hypothetical current state of the theoretical coastal aquifer with pollution and salinization problems, the fresh water supply of which is to be maximized, is shown in Fig. 3. The operation of 3 existing pumping wells (X_1=501m, Y_1=631m, X_2=1321m, Y_2=1012m, X_3=1081m, Y_3=1351m, radius of 0.25m), with the mission to supply a constant flow rate of 250L/s of clean drinking or irrigation water (versions), leads to seawater intrusion through the coastline and the salinization of well 2 and the pollution of well 3 by the initially circular plume (center: 752m, 1952m and radius=70m), before the study period (1000d) expires.

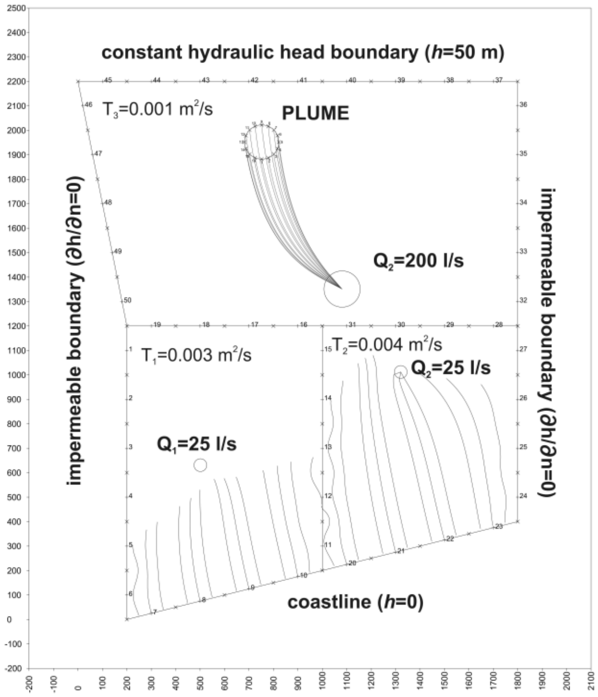

Fig. 3. Theoretical polluted coastal aquifer under study.

In version B1a the optimal implementation of the use of up to two additional abstraction wells (radius of 0.25m), of predefined minimum (10L/s) and maximum flow rate each (120L/s), together with the proper flow rate attribution to three existing wells (maximum 250L/s each) is studied, in order to ensure uninterrupted provision of maximum total fresh water flow rate during 1000d. The additional wells in combination with the existing pumping scheme can retard or avert polluted water (HC), but not pump it for treatment (PAT), as allowed in cost minimization problem versions A1 and A2 [10]. The proposed solutions must not entail wells' pumping of pollutants or seawater during a time-period of 1000d (PTM criterion of salinization).

Version B1b refers to the problem of maximizing the total fresh water supply (pumping) with no existing wells in the coastal aquifer. The algorithm is asked to propose locations and flow rates for up to five new wells (10L/s min to 120L/s max of flow rate) in order for the water supply to be the maximum possible with no pumping of pollutants or seawater by any well during 1000d (PTM criterion of salinization).

Finally, the third problem version B2b shares the same features as B1b with the no-salinization constraint being stricter, implying zero sea intrusion (seawater inflow from the coastal boundary elements = 0), rather than prevention of wells' pumping of seawater during 1000d.

3.2.1 Genetic Algorithm's parameters and chromosome structure

Following previous research, the optimization tool is simple GAs including elitism with binary representation of the chromosomes (potential problem solutions). Each chromosome, up to 82-digit long in version B1a (depending on total number of wells proposed, Fig. 4a) and 145-digit long in versions B1b and B2b (string length SL= up to 82 and SL=145, respectively, Fig. 4b) represents the coordinates of the new wells and flow rates of all wells (version B1a) or the coordinates and flow rates of new wells (version B2b).

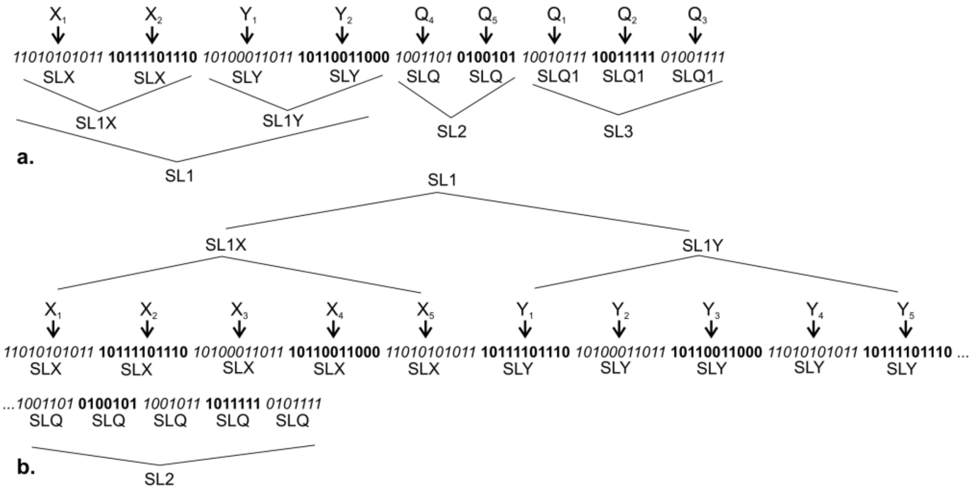

Fig. 4. Typical a) 82-digit (B1a), and b) 145-digit, chromosome, representing proposed solutions of the studied water supply maximization problems.

The generic operators used are selection (tournament procedure) [10], crossover and mutation/antimetathesis [21]. The genetic parameters used are: population size PS=50, number of generations NG=500, selection constant KK=3, crossover probability CRP=0.4, mutation probability MP=0.026 [7-10].

3.2.2 Objective Function

Optimization of the pumping scheme in the current water supply maximization problem version implies maximization of the evaluation function (fitness value FV of proposed solutions) which represents the total pumped fresh water flow rate (provided there is no penalty imposed in a proposed solution). Moreover a penalty function (Penalty) is included in the evaluation function (added to the total flow rate) to reduce a chromosome's fitness value, in case the respective solution violates the constraints. FV is given by:

$$FV = \sum_{i=1}^{N_w} Q_i - \text{Penalty} \tag{4}$$

where, N_w is the number of all wells, Q_i is the flow rate of well I, and Penalty is the penalty function.

The maximization problem can be outlined as follows:

Find Q_i, X_j, Y_j, i=1,5, j=1,5 (B1b, B2b) or j=4,5 (B1a) so that FV=ΣQ=Max

Constraints: (5)

$Q_1+Q_2+Q_3=250$L/s (B1a only)

$10\text{L/s} \leq Q_i \leq 120\text{L/s}$, i=1,5 (B1b, B2b) or i=4,5 (B1a)

(X_i, Y_i), i=1,5 (B1b, B2b) or i=4,5 (B1a) ϵ Permitted Zones (Fig. 2)

Penalty if pollution particles reach any well (See Par. 3.3.2)

Penalty if seawater particles reach any well (B1a, B1b, see Par. 3.3.2)

Penalty if there is seawater inflow to aquifer (B2b, see Par. 3.3.2)

In the aforementioned constraints, wells 1 to 3 are the existing ones in version B1a, while wells 4 and 5 are the additional ones. In versions B1b and B2b all wells (1 to 5) are new. Q_i, X_i and Y_i are the flow rates of coordinates of wells, respectively. FV is the chromosome's or solution's fitness value, which is equal to the total fresh water pumped flow rate of a penalty-free solution. The permitted zones are presented in Fig. 2.

3.2.3 Penalty Function (Penalty)

Each time a proposed solution leads to constraint violations, a penalty is imposed to its FV (subtracted). Violation can mean pollution of any well by plume particles or salinization of any well by seawater particles (B1a, B1b), or seawater inflow from the coastline (B2b). Penalty depends on the number of violated constraints (number of plume particles polluting any well and number of seawater particles polluting any well -B1a, B1b- or number of coastline boundary elements exhibiting seawater inflow -B2a) and also on the magnitude of the violation (consecutive number of timestep during which a plume particle pollutes an existing well and number of timestep during which a seawater particle pollutes any well in problem -B1a, B1b- or magnitude of seawater inflow per coastline boundary element -B2a).

Penalty in versions B1a and B1b is given by:

$$Penalty_1 = \left\{ \begin{array}{l} \sum_{i=1}^{N_{plume}^{viol}} \left[P_C + P_V \cdot \frac{(TP - t_i)}{TP} \cdot 100 \right] + \\ \sum_{j=1}^{N_{coast}^{viol}} \left[C_{coast} \cdot P_C + \frac{Sea_j}{Q_j} \cdot C_{coast} \cdot P_V \cdot \frac{(TP - t_j)}{TP} \cdot 100 \right] \end{array} \right\} \quad (6)$$

where, N_{plume} is the number of plume particles polluting a well, N_{coast} is the number of seawater particles polluting a well, P_C is the constant part of Penalty function, P_V is the coefficient of the variable part of the function, TP is the number of ΔTs (here TP=100), t_i is the ΔT during which plume particle i pollutes a well, t_j is the ΔT during which seawater particle j is pumped by a well, C is a coefficient of P_C and P_V in the seawater-related part of the Penalty function, aimed to express the relative weight between pollution and salinization of a well, Sea_j is the inflow (in L/s) of seawater that particle j represents, and Q_j is the flow rate of well that pumped particle j. Sea_j is given by:

$$Sea_j = \frac{Intr_k}{N_{ppBE}} \quad (7)$$

where, $Intr_k$ is the inflow (in L/s) of seawater from coastline boundary element k and N_{ppBE} is the number of particles per coastline boundary element (here N_{ppBE}=3).

$Intr_k$ is given by:

$$Intr_k = T_k \cdot \frac{\partial h_j}{\partial n} \cdot L_j \quad (8)$$

where, T_k is the transmissivity of zone k where coastline's boundary element j belongs to and L_j is the element's length.

In problem version A2 Penalty is given by:

$$Penalty_2 = \sum_{i=1}^{N_{plume}} \left[P_C + P_V \cdot \frac{(TP - t_i)}{TP} \cdot 100 \right] + \sum_{j=1}^{N_{elem}} \left[C \cdot P_C + C \cdot P_V \cdot Intr_j \right] \quad (9)$$

where, N_{elem} is the number of boundary elements through which seawater inflow occurs.

"Optimal" solutions entail Penalty=0, hence FV represents the total pumped fresh water flow rate (total water supply). Calculating P_C and P_V follows the minimum penalty rule [21]. According to the simple but computationally demanding rule, the fittest penalty function for the GA to find the global optimum solution is the lowest one which can consecutively provide penalty-free optimal solutions. The P_C/P_V ratio is set to 10/1 in all scenarios, in an attempt to balance the impact of the simplistic degradation of a solution just for violating a constraint with the more sophisticated variable part of the penalty which depends on the constraint violation extend.

4 Results

For each problem version, five runs of the GA were implemented, lasting at least 7h in a Intel(R) Core(TM) i7-4510U CPU @2.00 GHz PC. The optimal solutions for all three theoretical problem versions are algebraically presented in Table 2.

Table 2. Algebraic presentation of the optimal solutions for all three problem versions.

Result	Problem version		
	B1a	B1b	B2b
FV	394.902	831.176	402.000
ΣQ	394.902	831.176	402.000
Penalty	0	0	0
Q_1 (L/s)	39.216	113.529	11.882
Q_2 (L/s)	53.922	250	16.588
Q_3 (L/s)	61.765	246.235	122
Q_4 (L/s)	120	89.059	174.706
Q_5 (L/s)	120	245.294	76.824
X_1 (m)	501	410	483
Y_1 (m)	631	1913	1608
X_2 (m)	1321	1556	1099
Y_2 (m)	1012	1998	1996
X_3 (m)	1081	1584	417
Y_3 (m)	1351	1987	1988
X_4 (m)	406	460	1252
Y_4 (m)	1985	992	1999
X_5 (m)	1375	1578	1332
Y_5 (m)	1997	1999	1997

4.1 Problem Version B1a

Fig. 5 graphically presents the optimal proposed solution for version B1a. In this version the use of existing wells 1, 2 and 3 is a prerequisite, with the algorithm proposing the distribution presented, and a total flow rate from them equal to 154.903 L/s, 39.23% of the total pumped 394.902L/s. The additional wells 4 and 5, operating at maximum pumping levels (120 L/s), are located on both sides of the plume, spreading it as much as possible and retarding its advance towards the existing pumping scheme. On the other front, that of sea intrusion, given the fact that B1 problem versions define salinization as the pumping of sea water by any well, the solution is considered acceptable, since seawater particles entering the flow field get close but are not being pumped by the closest to the coastline existing wells 1 and 2. This is achieved through: a) placing the additional wells far away from the coastline and b) proper attribution of flow rates to the existing pumping scheme. This is actually the optimal implementation of a HC pollution-sea-intrusion manipulation technique in order to manage the studied coastal polluted aquifer, when existing abstraction wells are to be included in the scheme.

The unrealistic trajectories of the seawater particles that originate from the coastline's boundary element 20 are caused by their proximity to the poorly discretized internal boundary of zones 1 and 2, which constitutes an intrinsic BEM-related accuracy problem.

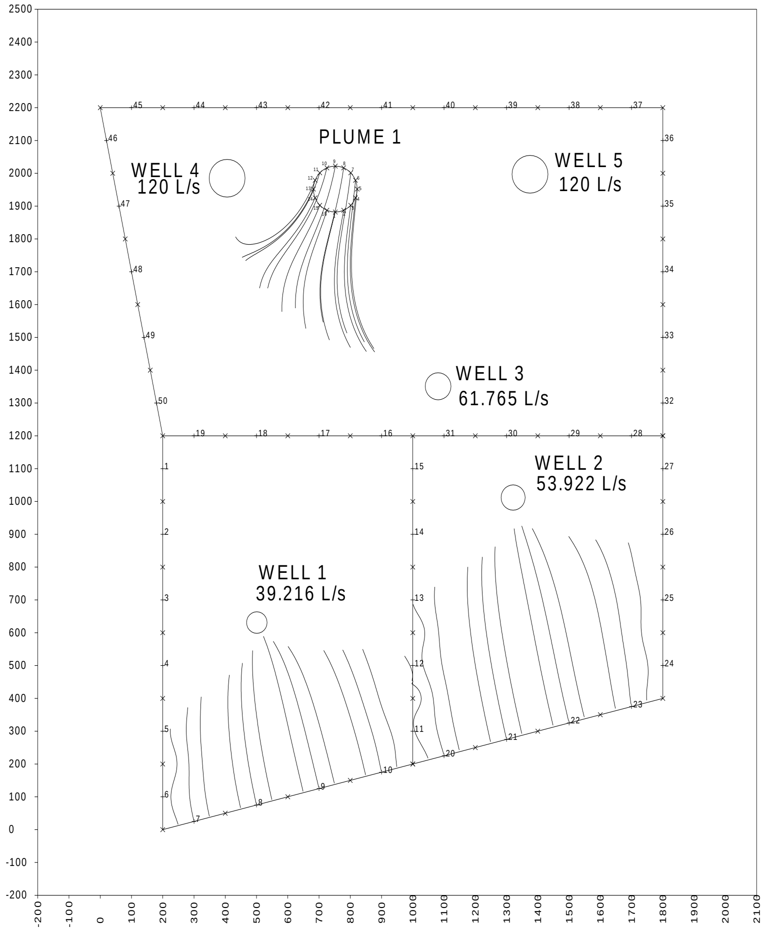

Fig. 5. Optimal solution for problem version B1a.

4.2 Problem Version B1b

Fig. 6 graphically presents the optimal proposed solution for version B1b. There are no existing wells here, so the GA freely proposes a pumping scheme of five new wells with a total water supply of 831.176 L/s, 210% of the respective total flow rate of version B1a, without pumping polluted or sea water. Four out of five new wells are located in Zone 3, one at the west side of the plume and a system of three wells at its east side, operating at maximum pumping rates (around 250L/s). The four of them together with Well 4, which is the only one located inside the adjacent to the coast zones, manage to spread the plume and retard its advance.

As far as the sea intrusion is concerned, despite the fact that there is inflow of sea water inside, not only into the coastal zones, but into Zone 3 too, seawater particles are not pumped by any well, during the 1000d period. This is another optimal HC technique, that allows maximum exploitation of the coastal aquifer without compromising pumped water quality for the studied time-period. One can again observe the unrealistic displacement of sea water particles near the internal and western external boundary, due to the small number of boundary elements used.

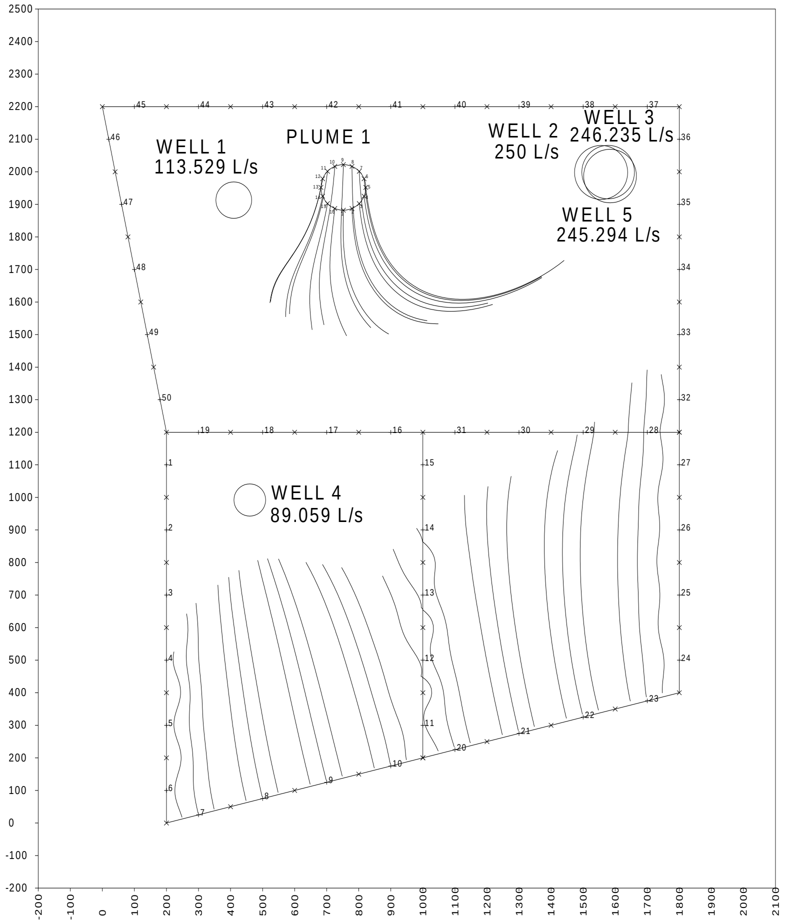

Fig. 6. Optimal solution for problem version B1b.

4.3 Problem Version B2b

Fig. 7 graphically presents the optimal proposed solution for version B2b, which resembles the previous one (B1b), with no existing wells, but the salinization constraint criterion relates to the prohibition of sea water inflow from the boundary elements of the coast rather than the contamination of wells in a given period of time. The GA proposes a solution with a pumping scheme of five new wells, all located in the northern zone (3), with four of them actually as north as possible, in compliance with the permitted zones of Fig. 2. The total water supply is 402L/s, higher than B1a, but a 48.37% of B1b's total pumped flow rate, as a result of the extremely stricter salinization zero inflow criterion.

At the north-east, three wells (16.588, 174.706 and 76.824L/s, respectively) attract a big portion of the plume, while another well operates at 113.529L/s in the north-west side of the field, at the other side of the plume, and together with Well 1 at the south-west of the plume, manage to hydraulically control (HC) the pollution, without pumping it during the 1000d studied period and also with no sea intrusion throughout the southern coast whatsoever. The proposed pumping scheme fully exploits the fresh water of the coastal polluted aquifer in an optimal fashion, as was the case in the previous scenarios.

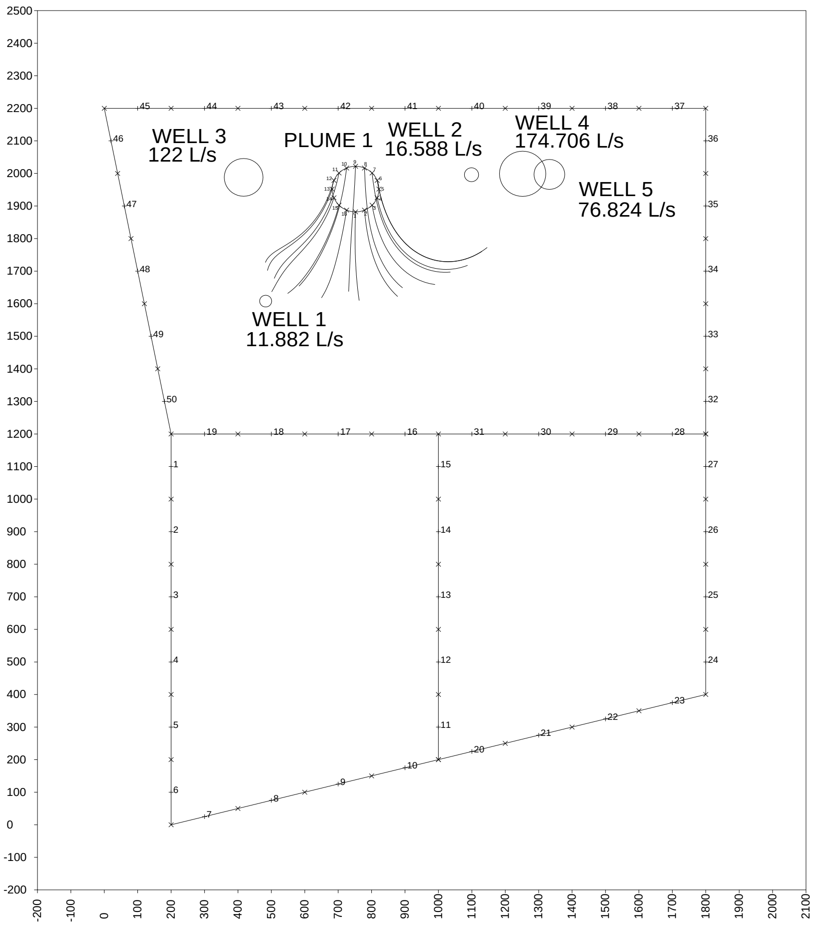

Fig. 7. Optimal solution for problem version B2b.

5 Conclusions

The method of GAs is once again proved to be an extremely powerful and effective optimization tool that can successfully provide optimal solutions at groundwater management problems. “Optimanage”, the authors’ own optimization software application, is a user-friendly tool that solves the general problem of optimal management of a coastal aquifer with pollution or/and salinization problems, using GAs, PTM and BEM. Apart from the optimization process, it has the ability to graphically present the produced optimal pumping schemes and the pollutant/seawater spread in the form of scaled maps and flow videos.

The graphical presentation procedure can be automated so that the users-researchers can produce and manage large numbers of ‘optimal’ solutions and simplify the process of discovery, identification and categorization of many different strategies in their algebraically optimal versions. In the same way that the app was successfully implemented in management cost minimization problems [7,8,10], in this water supply maximization problem versions, the automated procedure can produce a group of different strategies, which can is described by the authors as as “qualitative optimization”. Due to the complexity of these problems’ nature, in combination with the uncertainties emerging from the many simplifying assumptions and accuracy compromises of the 2D problem, this aspect of the optimization procedure that “OptiManage” includes are way more significant compared to the strictly algebraic minimization of the total cost.

That does not reduce the researcher to a simple user unquestioningly adopting the proposed solutions/strategies. The researcher’s important role is to adjust the algorithm and select the fittest GA, PTM and BEM parameters and to direct the GA to search the broadest field of possible solutions, find the largest number of different strategies (flow profiles, see [8]) in their algebraic optimal version, and, more importantly, finally select the most appropriate strategy version for the specific problem. The great pool of different strategies and different versions of them too, lets the user take into account not only the criteria and constraints included in the objective function, but possibly additional ones, too, a-posteriori.

The use of surrogate models for the flow field, mass transport, pollution of wells etc. simulation so as to adjust the computational load and, thus, time, raises accuracy issues. That renders the researcher/user's role even more critical, as all proposed strategies and "optimal" solutions should be logically checked. In addition, they should be re-simulated with a finer temporal discretization of the study period and with a finer discretization of the internal-external boundaries, so as to filter unrealistic solutions with unpractical features (e.g. wells of unpractically low flow rates, wells too close one to another, etc.).

Future research includes the optional use of additional recharge wells together with, abstraction wells, with a necessary inclusion of another term in the objective function (cost minimization) to investigate whether the total water supply can be further increased. Furthermore, a series of brief additional well's pumping sudden failure incidents can be studied, in order to stress test the existing solution profiles and conclude on their fail-safe attributes, filtering the most precarious of them. That could easily lead to the discovery of improved solutions (greater water supply) with addition of targeted intermissions in the wells' operation and indicate the possibility of the inclusion of intermittent pumping in the objective function of the GA.

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