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OPTIMAL GEOGRAPHICAL WELL POSITIONING IN AGRICULTURAL POLLUTED AREAS

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Summary. The extended use of organic and inorganic chemical fertilizers, animal waste and domestic effluents are the main sources of nitrate pollution in cultivated lands. In this paper, a new optimization formulation that provides the “best” strategy by optimally geographical positioning a number of injection/pumping wells to achieve containment of the nitrate plume is proposed by reducing the geographical extent of the polluted areas. The objective function is defined as minimization of the original polluted area. The proposed formulation requires evaluation of extreme large number of candidate well locations in order to achieve shrinkage of the contaminant plume. To overcome the computational burden, a Differential Evolutionary (DE) algorithm is properly used showing convergence flexibility.

1 AGRICULTURAL POLLUTION

The need to cover the food demand resulted in tremendous expansion of agricultural lands without avoiding subsistence farming practices[1]. Since the agriculture sector uses an average of 70% of the freshwater resources, those practices are mainly responsible for water consumption, sediment and water pollution in cultivated regions and they may adversely affect the natural environment and the quality of life of its inhabitants. Talking about water pollution, agriculture activity is treated as non-point source since the point of entrance into the water receiver is not obvious and the response to hydrological conditions is not easy to be measured or controlled and therefore difficult to be regulated[1]. The continuous application of fertilizers in conjunction with major irrigation schemes usually exceeds the capacity of the soil to retain and transform the nutrients. This results to a nitrogen or phosphate surplus in the soil that percolates into the subsurface water bodies and creates a non-point source pollution.

The containment of this plume and/or the required aquifer remediation is a high cost and time consuming process. The absence of water harvesting and collective irrigation system, especially in coastal agricultural regions has driven the farmers to heavily rely on subsurface water resources. Previous research work has shown that over-irrigation, non-practical scheduling of irrigation and an extended application of nutrients lead to low recoveries of water and nutrients and increase the expansion of existing nitrate plumes. Parameters such as the soil type, climatic factors and crop requirements need to be considered prior to any fertilizer and irrigation practices application[2]. Recent works reported in the literature have focused on the effect of mismanaged crop rotation, poor fertilization and irrigation policies. In their work, Darwish et al.[3] studied the human impact on land degradation through the integrated effect of fertilization and irrigation as well as the soil salinity focusing on the origin of it and the human response for different cropping patterns in a coastal region in Lebanon. Their results have shown that a rational management of irrigation and fertilization policies is necessary to improve their efficiency.

In coastal aquifers, the use of saline groundwater for irrigation is an option that becomes more and more realistic due the long time pumping activity that favors the seawater intrusion into the aquifers. Addressing this problem, Gonzalez Vasquez et al.[4] tried to determine the relationship between the cropping system and the observed nitrate concentration in the groundwater in the Province of Seville Spain. Their study shown that besides seawater intrusion, flood irrigation practices and super-fertilization practices on crops play an important role in salinization due to dissolution of soil minerals. A survey of groundwater quality across a broad area of the North China Plain proved the fact that the intense use of N-fertilizer and the widespread use of untreated groundwater for crop irrigation contribute significantly to the groundwater contamination problem. Also, the disposal of industrial and municipal wastes into streams contributes to the problem due to the fact that the pollutants can contribute to groundwater contamination through the infiltration process. However, the lack of data prevents evaluation of those sources[5]. The development of methodologies that ensure the rational and optimal management of the subsurface water resources will allow the containment of the nitrate pollution in aquifers that are heavily cultivated.

2 FIELD SITE CHARACTERIZATION

In the present study the area of interest is located in the Northern part of Peloponnese in the coastal region of Corinthian Gulf where besides the tremendous urban sprawl that is lately observed, an intensive agricultural activity takes place which results to water and sediment pollution due to the extended use of chemical fertilizers. The geology of the aquifer consists mainly of alluvial deposits along the coastline, limestone and some lenses of low permeability that considerably reduce the mitigation of pollution towards inland. As it is reported in previous works of Voudouris et al.[6] and Antonakos and Lambrakis[7], a large part of the area of interest is heavily cultivated mainly with olive trees, vineyards and fruit-bearing trees. The unconscionable use of nitrogenous fertilizers contaminates the groundwater since organic residuals remain in the soil for long time periods. In order to determine the extent of the contaminant plume an extensive sampling and analysis project was conducted that revealed the main reasons of the subsurface water pollution, which were: a) the irrational application of chemical fertilizers and irrigation doses and b) the use of septic tanks and the disposal of untreated domestic wastes into the aquifer through injection wells. In their analysis Voudouris et al.[8] concluded that a remediation period of 16.4 years is needed to restore subsurface water quality to a background level of 15 mg/l nitrates, enforcing a complete fertilization hold.

In the present study, a groundwater flow and nitrate mass transport model for the area of interest is developed in order to predict the long-term impact of water withdrawal and the nitrate contaminant migration into the aquifer and also to examine the water resources management alternatives A detailed description of the simulation model development including physical and numerical model parameters was presented by Papadopoulou et al.[9].

3 OPTIMAL ENVIRONMENTAL DESIGN FORMULATION

As it is concluded from previous works, in the area of interest the irrational use of fertilizers over long periods of time is responsible for the large number of non-point pollution sources resulting in an extended nitrate contaminant plume. For that reason, the first priority that engineers put on the table is the containment of the pollution. Containment of the nitrate pollution in an aquifer could be achieved using a hydraulic gradient approach, which is based on the concept of installing injection and pumping wells at specific locations and at certain depths inside and outside the contaminant plume. Depending upon the hydro-geological characteristics of the area, the operation of the well network is accordingly adjusted to achieve the containment and the shrinkage of the contaminant plume. The goal of this analysis is the shrinkage of the contaminated areas (contaminant plume) by determining the optimal geographical well locations in order to install the injection or/and pumping wells. The contaminated water will be transferred to a waste-water treatment plan for further processing. Herein the remediation period is considered equal to 15 years. The formulation of the optimization problem is based on the environmental constraints imposed by the local authorities regarding the water quantity and quality. For the numerical simulation of the physical system the Princeton Transport Code (PTC) was used, which is a subsurface water flow and contaminant transport simulator that solves a system of partial differential equations which represent the groundwater flow, the velocities and the contaminant mass transport. A finite element mesh of 1022 nodes and 1915 triangular elements was created to discretize the area of study (Fig. 1).

The goal of the optimization problem is to minimize the plume area by optimally positioning ten (10) remediation wells inside and outside the plume. The proposed problem formulation includes the following characteristics: a cost function equal to the area of the plume, a set of integer design variables corresponding to the mesh node numbers used as candidate positions for the remediation wells, a modified DE algorithm able to address a mixture of real and discrete values of design variables, and the PTC algorithm used to evaluate each candidate solution. The optimization problem is formulated as a minimization problem and the cost function has the following form:

$$\min f\,,\;\; f = Plume\_Area, \quad q_i = 2000\,m^3/d\,,\;\; i = 1,\ldots,k \tag{1}$$

where *Plume_Area* is the area of the plume, defined by the mesh nodes where the nitrate concentration is greater than 50ppm (c_{plume} > 50ppm), k is the number of remediation wells and q_i is the pumping rate in each one of the remediation wells, which could be positioned at any of the N=166 node points of the mesh around and inside the polluted area. The positions of these 10 pumping wells are the (integer) design variables of the optimization problem. The computation of *Plume_Area* is performed by checking the nitrate concentration of all mesh nodes (triangle elements) at the end of each simulation. If all 3 nodes of a triangle element have concentration higher than 50ppm, the corresponding triangle area is added to *Plume_Area*. If one or two nodes have concentration higher than 50ppm and the rest less than 50 ppm, a fraction of the triangle's area (where the nitrate concentration is c_{plume} > 50ppm) is added to *Plume_Area*; a linear variation of the concentration is assumed between the nodes of each triangle in order to compute this fraction of the triangle's area (Fig. 2). For simplicity reasons only pumping wells have been used in this study; however, a study combining pumping and injection wells is under development.

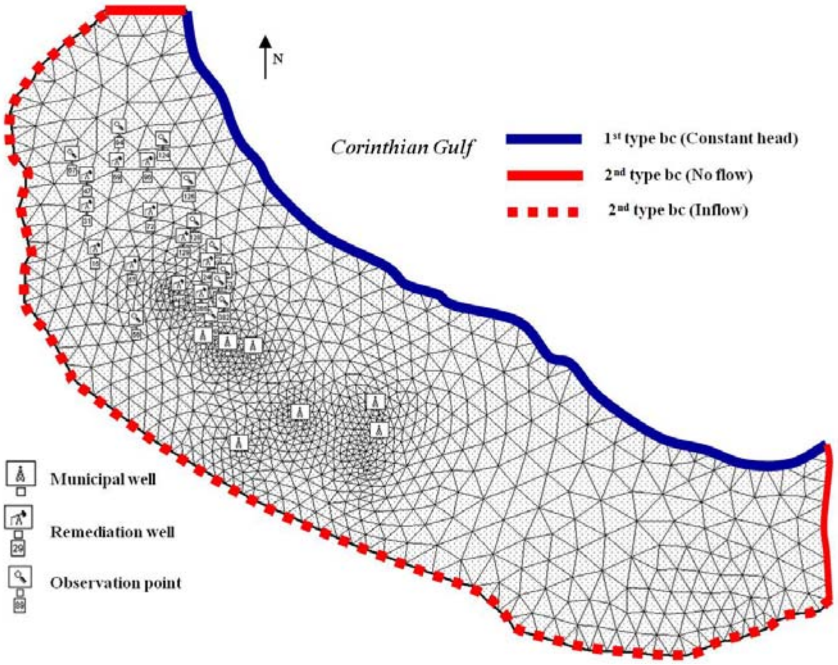

Figure 1: Model Discretization - Imposed Boundary Conditions[9]

The problem of finding the best 10 locations for the corresponding 10 remediation pumping wells out of 166 candidate mesh nodes results in $\frac{(N+k-1)!}{k!(N-1)!} = \frac{(166+10-1)!}{10!(166-1)!} = \frac{175!}{10!\,165!} = 5.7\cdot 10^{15}$ candidate solutions, which is considered as a huge number. The problem is solved using a Differential Evolution algorithm[10,11,12], which was constructed to handle both discrete and continuous values of problem's design variables.

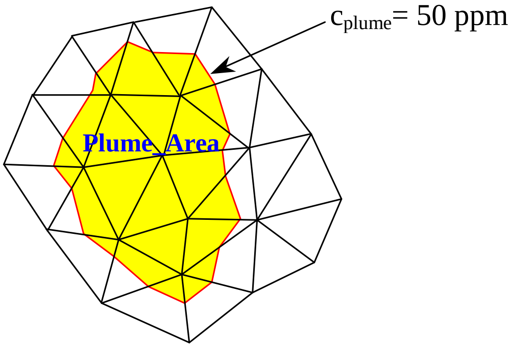

Figure 2: The plume area corresponds to a concentration higher or equal to 50 ppm

The standard DE algorithm uses a fixed size, randomly initialized population equal to n_{pop}. At each generation, a new population is produced. Each element of the current population may be replaced in the new population by a newly generated one, which is the result of successive mutation and crossover operators among the members of the current population. Given an objective function $f\left(X\right)$, the optimization target is to minimize the value of this objective function by optimizing the values of its design variables $X=\left(x_1,x_2,\ldots,x_{n_{param}}\right)$ where X denotes the vector composed of n_{param} design variables, which take values between specific upper and lower bounds. In order to obtain a starting point for the algorithm, an initialization of the population takes place, which is established by randomly assigning values to the design variables within the given boundaries. DE's mutation operator is based on a triplet of randomly selected different individuals. A new parameter vector is generated by adding the weighted difference vector between the two members of the triplet to the third one (the donor). The perturbed individual and the initial population member are then subjected to a crossover operation that generates the final candidate solution

$$x'^{(G+1)}_{i,j}=\begin{cases} x^{(G)}_{C_i,j}+F\cdot\left(x^{(G)}_{A_i,j}-x^{(G)}_{B_i,j}\right) & if\ \left(r\le C_r \vee j=k\right)\ \forall\ j=1,\ldots,n_{param} \\ x^{(G)}_{i,j} & otherwise, \end{cases} \tag{2}$$

where $x^{(G)}_{C_i,j}$ is called the "donor", G is the current generation,

$$\begin{gathered} i=1,\ldots,n_{pop},\ j=1,\ldots,n_{param},\ A_i\in\left[1,\ldots,n_{pop}\right],\ B_i\in\left[1,\ldots,n_{pop}\right],C_i\in\left[1,\ldots,n_{pop}\right] \\ A_i\ne B_i\ne C_i\ne i,\ C_r\in\left[0,1\right],\ F\in\left[0,1+\right],\ r\in\left[0,1\right], \end{gathered} \tag{3}$$

and k a random integer within [1, n_{param}], chosen once for all members of the population. F and C_r are DE control parameters, which remain constant during the search process and affect the convergence behavior and robustness of the algorithm. The population for the next generation is selected between the current population and the final candidates. If each candidate vector is better fitted than the corresponding current one, the new vector replaces the vector with which it was compared. The DE algorithm used in this analysis is accordingly modified to successfully address a mixture of real and discrete values of design variables. The user defines the step for each variable, which for real ones is denoted as 0 and for integers is equal to 1. Different values for the steps of the discrete design variables can be also used, according to the design problem under consideration. The main difference between the discrete and the standard DE algorithm is in the mutation operator where the values that are computed for the discrete genes of the mutated chromosome are modified to the closest discrete value of the corresponding design variable. Similar procedures are adopted when random values of the discrete variables are needed.

4 RESULTS AND DISCUSSION

In the DE optimization procedure, a maximum number of 200 generations were used for a population size (n_{pop}) equal to 30 (resulting in 6000 evaluations of candidate solutions), while F and C_r parameters[10,11] of the DE algorithm were set equal to 0.6 and 0.45 respectively. The convergence history of the DE algorithm is presented in Fig. 3. The final optimal solution corresponds to a plume area equal to 3,990,527m^2, compared to 4,200,913m^2 of the computed plume area of a non-remediation action (5% reduction). It is evident that the optimization procedure has not converged to its final optimal solution since in the final generation there is a cost function difference between the best and worst solution of the population. The optimization procedure was terminated in the 200th generation due to the very high computational cost (it took almost 4 weeks for the 200 generations). The reason for the large computational cost is the time consuming simulation of the flow and transport field for the 15 years of pumping activity, needed for every one of the 6000 candidate solutions evaluated by the DE algorithm.

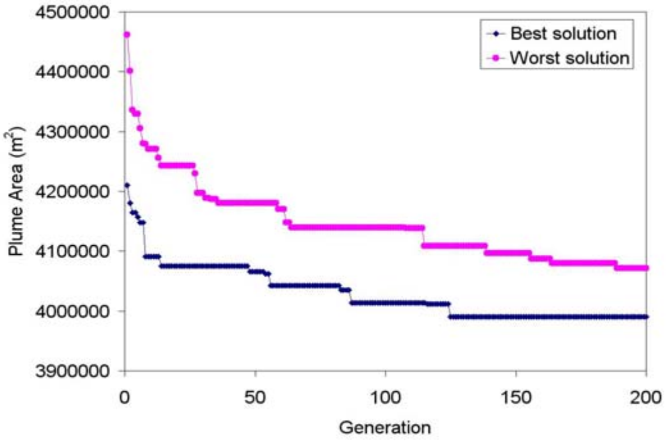

Figure 3: Convergence history of the DE algorithm.

The PTC simulation results for the (sub-)optimal solution are presented in Fig. 4, where the plume areas using the optimal well positioning (after the final winter and the final summer periods correspondingly) are compared with the reference plume area (if no remediation is performed). The optimal well positions are also presented. As it can be observed the application of the optimization procedure resulted in a containment of the plume inside a specific area, while an additional (small) reduction in this area was achieved. This reduction is by no means a trivial result, as far as the nitrate sources continue to pollute the soil for all 15 years of the remediation period.

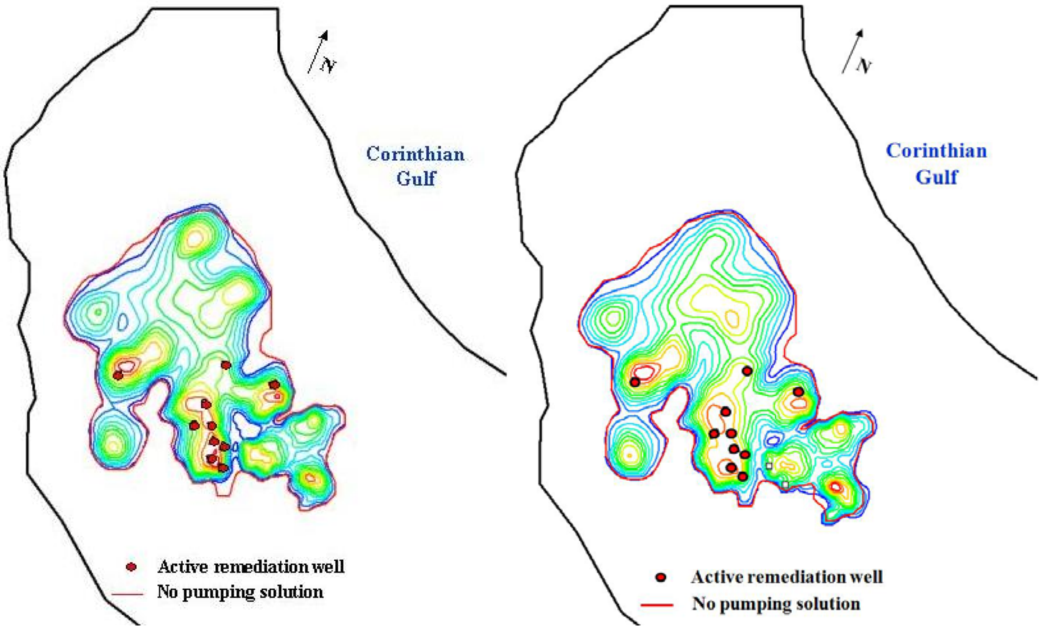

Figure 4: The plume area of the DE best solution at winter (left) and summer (right) after 15 years of treatment. The external red line corresponds to the plume area without pumping, after 15 years.

5 CONCLUSIONS

In this paper, a new formulation is proposed to obtain reduction of the nitrate polluted areas by optimal geographical positioning the remediation wells inside and outside the polluted region. The cost function to be minimized is the plume area, while the solution of optimization problem provides us with the ten optimal locations of the 10 remediation wells with fixed pumping rate over the 166 candidate locations. The numerical simulation of the groundwater flow and contaminant nitrate mass for each one candidate solution (well positioning) is computed using the PTC numerical simulator. A DE algorithm capable of handling both continuous and discrete design variables is used as the optimizer, which manages to converge to a (sub-) optimal solution, corresponding to a 5% reduction in the plume area. Taking into account the continuous pollution of the area of interest during the entire 15-year simulation period, the obtained results are not trivial. A very high computational cost associated with the simulation of the contaminant mass field was required for each candidate solution so a speed up of the optimization process is needed to render the methodology suitable for practical applications. Future work will involve acceleration techniques for the optimization procedure, the use of injection combined with pumping and the use of the pumping/injection flow rates as design variables, along with the positions of the remediation wells.

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