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Planning infrastructural measures for controlling saltwater intrusion in a coastal aquifer by Global Interactive Response Surfaces: the Nauru island case study

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Abstract: Infiltration galleries and scavenger wells are usually constructed to control pumping based saltwater intrusion in coastal aquifers. The optimal allocation of these infrastructures can be decided by solving a multi-objective optimization problem balancing availability of fresh water supply and installation/operation costs, where the effects of different design options on the planning objectives are simulated through a high fidelity model of the flow and transport processes. The incorporation of these simulation models within an optimization-based planning framework is not always straightforward because of the computational requirements of the model itself and the computational limitations of the optimization algorithms. In this paper we explore the potential for the Global Interactive Response Surface (GIRS) methodology to overcome these technical limitations. The GIRS methodology is used to recursively build a non-dynamic emulator of the process-based model that maps the design options into the objectives values and can be used in place of the original model to more quickly explore the design option space. The approach is used to plan infrastructural interventions for controlling saltwater intrusion and ensuring sustainable groundwater supply for Nauru, a Pacific island republic in Micronesia. GIRS is used to emulate a SEAWAT density driven groundwater flow-and-transport simulation model. The evaluation results show the potential applicability of the proposed approach for optimal planning of coastal aquifers.

Keywords: response surface; groundwater; optimization; salt intrusion

1 INTRODUCTION

Groundwater is the only freshwater resource in most oceanic islands and mainland coastal areas and its sustainable use is key to ensure the social and economic development of the region. The development of groundwater resources in coastal aquifers is a delicate issue and the expansion of the current extraction capacity requires a careful planning to avoid water quality degradation due to seawater intrusion [Ghassemi et al., 1996]. In many cases, encroachment of seawater arises when the aquifer is pumped beyond its natural recharge rate and the seawater is drawn into the system to maintain the groundwater balance. Generally, seawater intrusions can also occur as a localized phenomenon, when the excessive pumping at individual well lowers the potentiometric surface causing upconing of the fresh-saline water interface. These problems are very likely to occur with increased frequency in the future due to the sea level rise induced by the undergoing climate change, and atoll islands, with their low elevation above the sea level, are particularly vulnerable. Different infrastructural interventions can be implemented to limit and control seawater intrusion in coastal aquifers [UNEP, 1998], including scavenger wells and infiltration galleries. The design of these infrastructures is usually performed using an expert-based 'what-if' analysis over a limited number of design alternatives (e.g. combinations of extractor rate, location, and number of wells). The expert decisions balance availability of freshwater supply and installation/operation costs, where the effects of the different design options on the planning objectives are simulated by a high fidelity model of the flow and transport processes. The formulation of the design problem as a multi-objective optimization problem should, at least in principle, allow to explore in a more effective way the space of the feasible design alternatives and thus possibly find increasingly efficient solutions. However, the incorporation of high-fidelity simulation models within an optimization-based planning framework is not always straightforward because of the computational requirements of the model itself and the computational limitations of the optimization algorithms. A number of approaches have been investigated in the literature to combine optimal decision-making and high resource demanding groundwater process-based models. Aly and Peralta [1999] use a combination of an Evolutionary Algorithm and a neural network response surface to emulate a 3D flow-transport-diffusion model of the aquifer and optimize the number, location and extraction rate of a pump and treat well systems; Yan and B. Minsker [2006] use a 3D model of the aquifer combined with Adaptive Neural Network Genetic Algorithm to optimize the remediation of a contaminated (RDX and TNT) aquifer. Ferreira da Silva and Haie [2007] combine neural response surface and Genetic Algorithm to optimize, within a cost-benefit framework, position and extraction/injection rate of a pump and treat well system in a coastal aquifer. Kourakos and Mantoglou [2008] combine Genetic Algorithm and modular neural network to compute a global approximation of the Response Surface for deciding the extraction rate sequence in a coastal aquifer. The simulation model is SEAWAT. Finally, Sreekanth and Datta [2006] combine Evolutionary Multi-Objective methods and ensemble of neural networks surrogates to optimize the extraction of freshwater in a costal aquifer composed of 8 extraction wells and 3 barrier well. In this paper we investigate the use of the Global Interactive Response Surface (GIRS, see Castelletti et al. [2010]), a new methodology recently tested in lake water quality remediation problems [Castelletti et al., 2011], to design infrastructural interventions for preventing salt intrusion in a coastal aquifer. The GIRS methodology is used to recursively build a non-dynamic emulator of a 3D groundwater model that maps the design options into the objectives (cost, water quality and quantity) and can be used in place of the original model to more quickly explore the design option space. The approach is used to plan infrastructural interventions for controlling saltwater intrusion and ensuring sustainable groundwater supply for Nauru, a Pacific island republic in Micronesia. GIRS is used to emulate a SEAWAT density driven groundwater flow-and-transport simulation model.

2 GLOBAL INTERACTIVE RESPONSE SURFACE METHODOLOGY

Consider a planning project in which we need to fix the values of n decision variables u_k with $k = 1, \ldots, n$ (e.g. number and position of scavenger wells). An infrastructural intervention (alternative) is univocally represented by a decision vector $\mathbf{u}$ defined over a feasibility set $U \subseteq \mathbb{R}^n$ reflecting any physical constraint on the decision values (e.g. minimum distance from the coast line). The set of the Pareto efficient interventions can be obtained by solving the following optimization problem

$$\min_{\mathbf{u} \in U} \mathbf{y} = \mathbf{f}(\mathbf{u}) \tag{1}$$

where the vector $\mathbf{y} \in \mathbb{R}^m$ includes m performance indicators (objectives) that measure the satisfaction of economic, water quality and quantity targets following the implementation of an infrastructural measure, and the map $\mathbf{f} : \mathbb{R}^n \rightarrow \mathbb{R}^m$ represents all the physical and legal connections in the system that relate input and output. In this paper we will

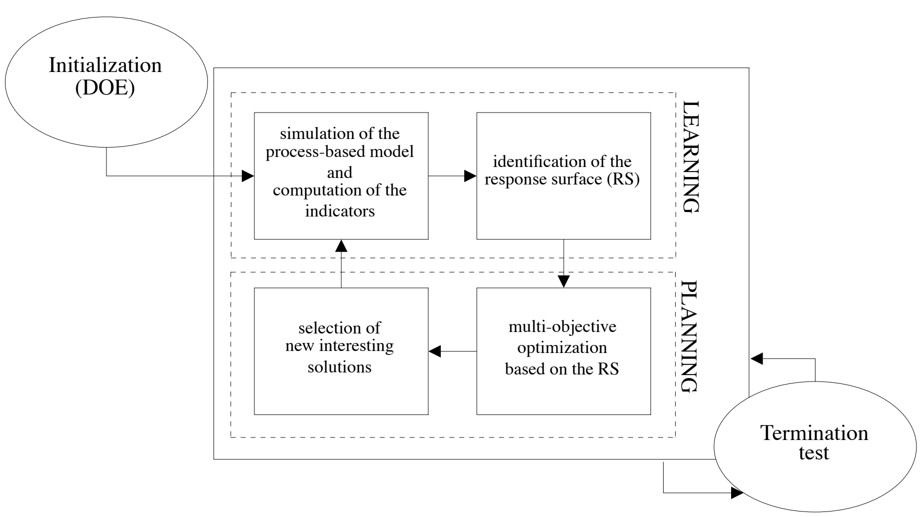


Figure 1: The learning and planning procedure implementing the Global Interactive Response Surface methodology.

consider a large class of problems where the relation $\mathbf{f}(\cdot)$ can be reproduced in a highly accurate fashion via simulation of a process-based model but the computational complexity of such model makes it impossible to solve problem (1).
For such class of problem, the Response Surface (RS) methodology (originally proposed by Box and Wilson [1951]) can be used to derive an approximate solution through the following two steps: (i) a data set of input and output is generated through a set of suitably designed experiments (in our case, this means simulating the system with the process-based model); and (ii) statistical inference techniques are applied to identify an approximate input-output relation $\hat{\mathbf{f}}(\cdot)$ (the response surface) to be used in place of the original relation $\mathbf{f}(\cdot)$ to solve problem (1). These steps can be performed in a iterative way, in fact, the results of the optimization phase can be exploited to select the regions of the decision space that it is worthwhile further exploring to derive more and more accurate approximations of the original simulation model.
Following this idea, in this paper we test the Global Interactive Response Surface (GIRS) approach (see Castelletti et al. [2010]), an iterative procedure where the phase of learning (identification of the RS) and planning (solution of the optimization problem) are developed in parallel. Each iteration, say the k-th, foresees performing the following steps: (i) to run N_k simulations of the process-based model to derive N_k output vectors $\mathbf{y}^1, \ldots, \mathbf{y}^{N_k}$ against N_k inputs $\mathbf{u}^1, \ldots, \mathbf{u}^{N_k}$; (ii) to identify the RS $\hat{\mathbf{f}}^k(\cdot)$ via interpolation of all the input/ouput data generated up to the current iteration; (iii) to solve the MO optimization problem (1) where $\mathbf{f}(\cdot)$ is replaced by the currently available RS $\hat{\mathbf{f}}^k(\cdot)$; (iv) to analyze the Pareto frontier based on the RS and select N_{k+1} Pareto-efficient solutions to be simulated at the following iteration. The procedure is sketched in Figure 1. As it can be noticed from the figure, the procedure is completed by an initialization phase, in which the first N_0 input vectors are chosen, e.g. using Design of Experiment (DOE) techniques; and a termination test, which indicates when the procedure can be stopped, e.g. because the average distance between the output vectors simulated via the process-based model and computed by the RS goes below a given threshold.

3 THE CASE STUDY AREA

Nauru is an uplifted limestone country island in the central Pacific Ocean (Figure 2). The island is a 22 km^2 raised atoll standing 4300 m above the ocean floor with a maximum land-surface altitude of 71 m above the sea level. Nauru is surrounded by a fringing coral reef between 120 and 300 m wide. The reef drops away sharply on the seaward

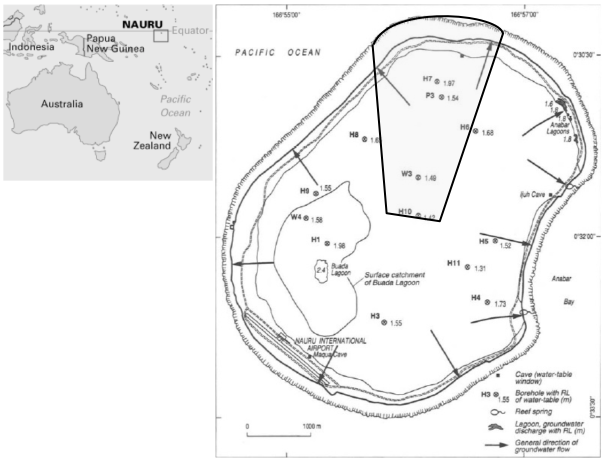


Figure 2: The Nauru island in the central Pacific Ocean. The study area considered in this paper is indicated by the black polygon. Source: [Jacobson and Hill, 1993].

edge, at an angle of about 40°, to a depth of about 4000 m. The land area consists of a narrow coastal plain or 'Bottomside', ranging from 100 to 300 m wide, which encircles a limestone escarpment rising about 30 m to a central plateau, locally known as 'Topside'. Groundwater is the only permanent freshwater resource available on the island and most of the water supply is dependent on imported water. As reported in Jacobson and Hill [1993], the island is underlain by a lens of often slightly brackish freshwater as much as 7 m thick; average thickness is 4.7 m. More recent groundwater investigations [Falkland, 2009] conducted in the dry season reported of a small freshwater lens in the north of the island, situated in the districts of Ewa and Anetan. This area consists of a sandy layer till the depth of 5-7 m from ground level, overlying a dolomitic limestone bedrock: salt concentrations monitoring revealed freshwater till a depth of 6 m, even during serious droughts such in 2010, thus making this lens a reliable freshwater reserve. Water extraction from groundwater is still underdeveloped, however any attempt at augmenting freshwater pumping must be accurately planned in order to limit associated potential seawater intrusion. Given the nature of the aquifer, the infiltration gallery technology appears as the most suitable solutions for controlling saltwater encroachment [UNEP, 1998]. Infiltration galleries (also called horizontal wells) skim the groundwater off the surface of the aquifers where water is fresher. Screened tubes are lain over 100 m length, in a shallow trench filled by high conductive gravel. At the center of the horizontal well a pump is placed in a small concrete basin connected to the screened tubes. Thanks to the length, the pumping effect is distributed in a wider area compared to vertical wells, decreasing head loss in the aquifer and avoiding or limiting salt water intrusion. Generally there are two types of infiltration galleries: open trenches and buried conduits. Open trenches are not generally recommended in areas with high potential contamination from surface pollutant sources, where instead the buried conduit systems offer better pollution minimization potentials [UNEP, 1998]. In Nauru case study, the potential area in which infiltration gallery is to be installed is densely inhabited (about 1180 people) so buried conduits should be more effective in avoiding fecal contamination. More specifically, we study the design of a horizontal gallery to be installed orthogonal to the main groundwater flow direction from the cliff line ('Topside') to the coast line (see Figure 2).

3.1 Decision variables

Three decision variables are considered: the location Y, its length L, and the pumping rate q. For each variable, the set of feasible values must be specified. In this study, these are finite sets of uniformly spaced values between a minimum and a maximum value obtained on the basis of empirical considerations, model requirements and previous works. Specifically, the definition are as follows:

Y [m]: Spatial position of the central point of the infiltration gallery (UTM 84 South Projected Coordinates). Minimum: 9944161 m (the line of the cliff). Maximum: 9944351 m (the coast line). Interval size: 5 m (the smallest spatial resolution of the model used in this study (see Section 3.3)).

q [m^2/day]: The pumping rate for meter in the gallery. Minimum: 0.1 m^2/day (see Falkland [1994] for Home Island in the Coco Islands). Maximum: to 1.5 m^2/day (see Falkland [1994] for Aitutaki Island in the Cook Islands). Interval size: 0.1 m^2/day.

L [m]: The length of the infiltration gallery [m]. Minimum: 20 m. Maximum: 300 m (the conventional maximum length for limestone islands [UNEP, 1998]). Interval size: 10 m (the smallest spatial resolution of the model used in this study (see Section 3.3).

The total number of feasible alternative combinations is 16,965. Since a simulation run of the process-based model takes about 2-3 hours (using an i5 Core Processor), an exhaustive search of the alternatives set would take almost 5 years.

3.2 Objectives

The optimal design of the horizontal gallery is formulated as a multi-objective optimization problem dynamically constrained by the model of the aquifer (see Section 3.3) and by the feasibility set of the decision variables. The three objectives considered are the minimization of the cost (installation and subsequent management of the gallery system), the minimization of the average concentration exceeding a freshwater threshold concentration (1.5 kg/m^3 as defined by the World Health Organization), and the minimization of shortages and surplus in freshwater supply with respect to the water demand for civil use The *cost* objective (euro) is the sum of the installation cost, given by the excavation cost (C_{exc}) and the cost of the drainage material (C_{dra}), and the management cost (C_{man}). The excavation cost C_{exc} is a function of the gallery length L and the excavation depth, which in turn depends on the spatial position Y of the gallery as the ground level elevation varies along Y. The drainage material cost C_{dra} is linearly proportional to the volume to be back-filled, which depends on the gallery length L only. Finally, the management cost C_{man} is related to the decision variables L and q, which determine the total water volume to be pumped and thus the energy cost.

$$y_1 = C_{exc}(L, Y) + C_{dra}(L) + C_{man}(L, q) \tag{2}$$

The *water quality* objective is the average concentration excess in the central point of the gallery with respect to freshwater limit concentration. Letting N be the number of times in the simulation horizon when the modelled salt concentration C_i (kg/m^3) exceeds the limit concentration C_{lim}, and d_i the duration (days) of the relevant transport time step, then the average concentration excess (kg/m^3) is

$$y_2 = \frac{\sum_{i=1}^{N}(C_i - C_{lim})\; q\; L\; d_i}{\sum_{i=1}^{N}\; q\; L\; d_i} \tag{3}$$

Objective J_2 is thus directly influenced by the decision variables q and L and, through the model simulation, indirectly affected by all the decision variables. The *water supply* objective is the total deficit/surplus freshwater volume (m^3) in the simulation horizon with respect to an estimated water demand of $W = 24$ m^3/day. Both water deficits and surplus are penalized, but the former are given a weight higher than the latter (specifically, $w_{def} = 0.8$ and $w_{sup} = 0.2$). The horizontal well is supposed to be operated only when the salt concentration C_i is below the limit concentration C_{lim}. Letting M be the number of times when this condition is satisfied, and d_i the duration of the relevant time step, then the objective is

$$y_3 = \sum_{i=1}^{M} w_{def} \cdot \max(\ W\ d_i - q\ L\ d_i,\ 0\ ) + w_{sur} \cdot \max(\ q\ L\ d_i - W\ d_i,\ 0\ ) \tag{4}$$

Again, the objective directly depends on q and L and, through the model simulation, on all the decision variables.

3.3 Simulation model

SEAWAT2000 [Langevin et al., 2003] is a three-dimensional finite-difference density-dependent model developed by USGS to simulate groundwater flow and transport of solute through a porous medium. SEAWAT2000 couples groundwater flow equations in MODFLOW2000 and solute transport equations in MT3DMS. MODFLOW2000 is a modular three-dimensional finite-difference groundwater flow model, while MT3DMS is a modular 3D transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems. In order to simulate the action of an infiltration gallery in the north zone of Nauru, SEAWAT2000 was calibrated using the hydraulic head and saline concentration distribution surveyed in November 2009. The model consists of a 112 $\times$ 86 cell grid: row spacing is varying from a minimum of 5 m in the infiltration gallery installation area to 200 m in the center of the island, while column spacing is varying from 10 m in the area of interest to 50 m. For the vertical discretization, 23 layers are set with a spacing varying from 0.5 m near the ground level to 5 m till a depth of 70 m under the average sea level. Nauru experiences widely variable rainfall mostly influenced by the ENSO phenomenon. Generally, dry periods last between 18 and 24 months. The worst case is when, after a dry period, a short period of rains (about 6 months) is followed by a new dry period, as it happened in 1984-90, 1994-99 and 2007-11. In this study, we used a simulation period of 5 years subdivided in stress periods of 1 month. The rainfall data registered between September 1994 and August 1999 were used to calculate the recharge rate for the model stress periods.

4 Results and discussion

The GIRS methodology was applied with the ultimate goal of finding improved solutions at no additional computational cost with respect to those (black points in Figure 3b) obtained via 'what-if' analysis by a field expert from Politecnico di Milano. To this end, the GIRS approach is run using nearly the same amount of simulations employed by the expert (i.e. 20 alternative as in Figure 3a) and so the approach is forcedly terminated when the number of simulation runs suggested nearly equals 20. The initial sample data set of input (decision) and output (objective) values is built using a subset of the alternatives simulated by the expert (the 8 extreme points of the decision feasibility set and 2 other alternatives randomly selected) and 2 additional alternatives chosen in such a way to cover in a fairly uniform way the feasibility space. The cost objective is independent from the system simulated behavior and can be directly computed with equation (2). At the first iteration of the GIRS approach, the response surface approximation of objectives (3) and (4) was obtained using piece-wise linear functions for both the water quality (R^2=0.6) and the water quantity objective (R^2=0.9). The associated approximated Pareto front is reported in Figure 3b (dark blue), along with all the objective values (light blue) computed from all the feasible alternatives (light blue in Figure 3a) using the response surface approximation. Among these solutions, the expert choose 9 interesting alternatives, which were simulated with SEAWAT2000. Seven out of nine of these alternatives turned out to be Pareto-efficient solutions. The performances of the Pareto-efficient solutions obtained

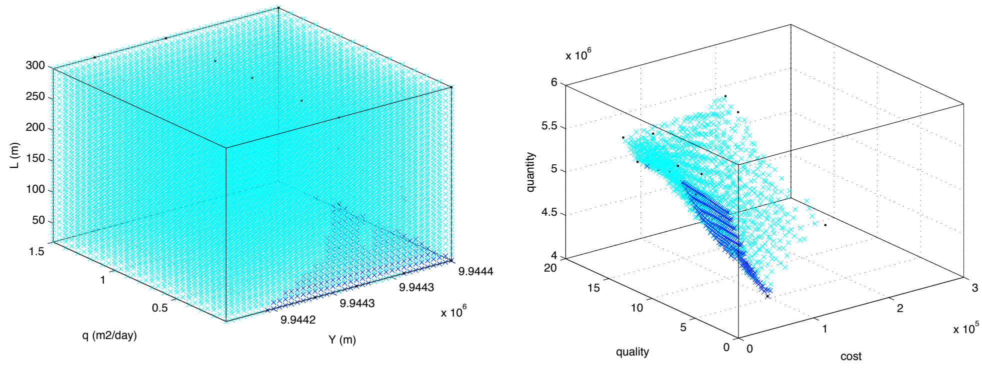
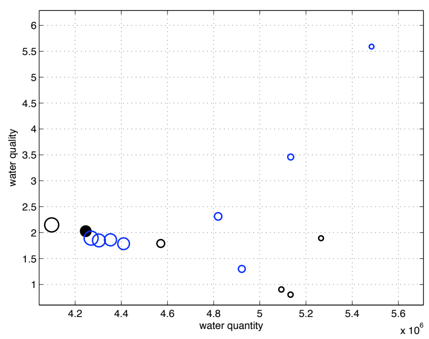


Figure 3: *Panel b*: the alternatives chosen by the expert (black points), the alternatives explored with the response surface at the first iteration of the GIRS approach (light blue), and the Pareto-efficient alternatives among these (dark blue). *Panel b*: the performances associated to the alternatives in *panel a*.



(a)

q [m2/day]	L [m]	Y [m]	Ctot [€]	Quality [kg/m3]	Quantity [m3/day]
0.1	*20*	*9944351*	*2257*	*6.6833*	*5484000*
0.1	*160*	*9944256*	*62065*	*2.027*	*4246100*
0.1	20	9944271	7267	0.904	5093200
0.1	20	9944311	4342	1.8914	5265400
0.1	20	9944256	7758	0.8044	5132900
0.1	90	9944256	34911	1.7899	4571000
0.1	250	9944256	96976	2.1488	4098400
0.1	130	9944276	46201	1.8507	4303100
0.1	80	9944306	18872	2.3124	4819200
0.1	110	9944271	39969	1.7859	4410100
0.1	140	9944266	51999	1.8948	4269300
0.1	120	9944281	41707	1.8626	4353500
0.1	40	9944261	15184	1.3003	4922000
0.1	30	9944346	36262	5.5894	5483800

(b)

Figure 4: The performances of the Pareto-efficient alternatives obtained by the expert (black circles in panel a and normal text in panel b) and the GIRS methodology (blue circle in *panel a* and grey shaded area in *panel b*). The filled circles in *panel a* and italics in *panel b* are the efficient alternatives found by both the approaches.

by the expert and those computed using the GIRS approach are reported in Figure 4. At the same computational cost, the GIRS approach was able to single out more solutions than the expert and, more importantly, mostly concentrated in the compromise region of the Pareto-front where generally solutions not only efficient but also fairly balanced among the objectives.

5 Conclusions

In this paper the Global Interactive Response Surface (GIRS) approach is adopted to optimally designing a horizontal gallery for controlling saltwater intrusion in the aquifer of Nauru, a Pacific island republic in Micronesia. Preliminary results show that GIRS is capable of obtaining a higher number of approximated Pareto-efficient solutions at no additional computational cost with respect to an expert running a 'what-if' analysis over the same amount of model simulation runs. Future research will explore the space for improvement by increasing the number of simulation runs and fully exploiting the potential of the GIRS methodology to emulate high-resource demanding models.

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