PLANNING ACTIONS FOR CONTROLLING SALTWATER INTRUSION COUPLING SEAWAT AND GLOBAL INTERACTIVE RESPONSE SURFACE: THE NAURU ISLAND CASE STUDY

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Introduction

Several infrastructural interventions can be implemented to limit or avoid seawater intrusion in coastal aquifers, including scavenger wells and infiltration galleries. Their optimal design can be decided by solving a multi-objective optimization problem balancing freshwater availability and costs, simulating the effects of the options with a density dependent flow-transport model. The integration of these models within an optimization-based planning framework is not always straightforward due to computational limitations of the model and of the optimization algorithms. Combinations of optimal decision-making and high resource demanding groundwater models on coastal aquifers have been explored widely in literature (Ferreira da Silva and Haie, 2007; Kourakos and Mantoglou, 2008). In this study it is investigated the use of a new methodology, the Global Interactive Response Surface (GIRS) (Castelletti et al., 2010), to design solutions for preventing saltwater intrusion. GIRS procedure is used to iteratively build a non-dynamic emulator of a 3D groundwater model, relating the design options and the objectives and can be used in place of the original model to quicker explore the design option space. This approach is used to plan an infiltration gallery to control seawater intrusion, ensuring sustainable groundwater supply for a small Pacific island. GIRS is used to emulate MODFLOW-SEAWAT2000. Results show the applicability of the GIRS approach for optimal planning in coastal aquifer cases, comparing to classical 'what-if' expert-based analysis.

Global Interactive Response Surface Method

This work presents some results of the NAURU project, funded by EXPO 2015, which has the objective to improve groundwater resources development in Pacific small islands [1]. This paper is focusing on the design of an infiltration gallery using, as process-based model, MODFLOW-SEAWAT2000, a 3D density-dependent flow-and-transport model developed by USGS. Nauru Republic (figure 1) is a small limestone island located in Central Pacific area, that suffers of periodic droughts due to ENSO (El Niño-Southern Oscillation) effects. The fresh groundwater (GW) resource is very limited, represented by small lenses few meters thick. GW flows radially from the center of the island toward the sea with gradient of 0,02% (figure 2) . Due to huge hydraulic conductivity (>500 m/d) of the limestone, fresh water mixes very fast with saltwater. Consequently the thickest lenses (5 m) were found only along coast line (figure 3) where fine sand sediments having a lower K (10 m/d) could store fresh water for a longer period (Alberti et al., 2011).

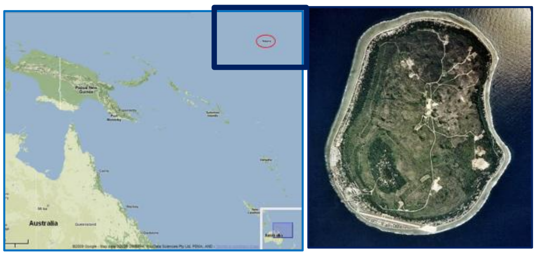

Fig. 1 - Nauru Island in Central-West Pacific Ocean

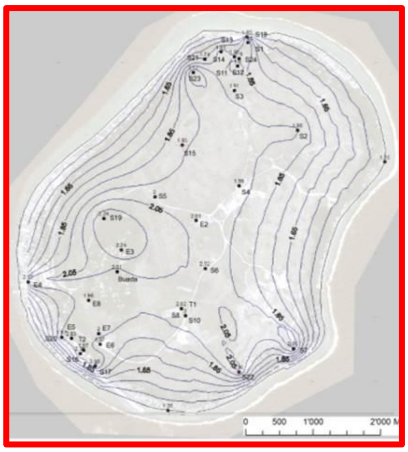

Fig. 2 - Piezometric contour map (November 2011)

Salt concentrations distribution in GW were simulated through a calibrated SEAWAT model implemented for the half north part of the island where was found one of the main fresh water lens. Thanks to model results, infiltration galleries were selected as the most suitable technology for this case. The gallery is to be installed orthogonally to the main flow direction, considering three variables: the location *Y* (distance from the coast line), its length *L* and the pumping rate per unit of length *q*. The alternatives are discretized over a finite domain. Every option is simulated with SEAWAT over a 5 years horizon using constant pumping rate. Since total number of feasible alternatives is 15,000, an exhaustive search with SEAWAT is computationally expensive (at last 12 hours for a single simulation run). The three objectives (outputs) considered are the following: minimization of the cost for cubic meter of freshwater extracted (*unitary cost*), minimization of the average concentration exceeding freshwater threshold concentration (*water quality*) and minimization of a weighted sum of daily shortages and surplus (since no water storage is possible at the moment on the island) in freshwater supply with respect to water demand for civil use (*water quantity*), using different weights for deficit (0.8) and surplus (0.2).

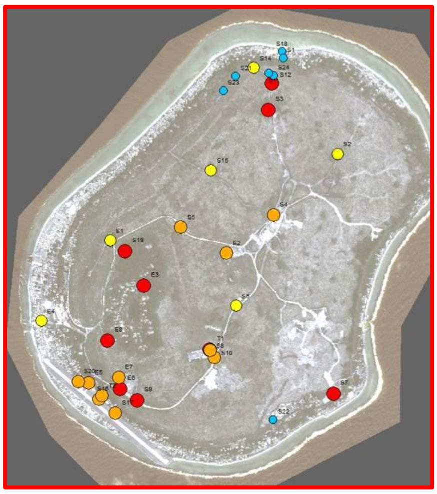

Fig. 3 – Salt concentration map (November 2011). Colormap varies from blue (freshwater, less than 1500 mg/L TDS) to red (saltwater, more than 10000 mg/L TDS). The biggest freshwater lens was found in the north of the island with 5 to 7 m thickness.

In a planning project, an alternative is univocally represented by a vector of decision variables. The set of the efficient solutions can be obtained by solving a multi-objective minimization problem (MO) of a performance indicators (objectives) set of economic, water quality and quantity targets via a function relating inputs and outputs (I/O relation). This relation is reproduced accurately through a process-based model but its computational complexity makes it impossible to solve the MO problem. To overcome such limitations, in this work, Global Interactive Response Surface (GIRS) approach was tested. Based on the Response Surface (RS) method, originally proposed by Box and Wilson (1951) it performs in an iterative way the following steps (figure 5): an initialization phase where initial input dataset is chosen; a learning phase in which indicators are computed via simulation of a set of alternatives with the process-based model to identify an approximate I/O relation (e.g. the response surface, RS) via interpolation of I/O simulated; finally a planning phase, where the MO problem is solved replacing original I/O relation (e.g. the process-based model) with the RS and then the Pareto front (e.g. the set of solutions for which no other alternative is better for all the objectives) is analyzed to select efficient solutions to be simulated at the following iteration. Procedure is completed by a termination test.

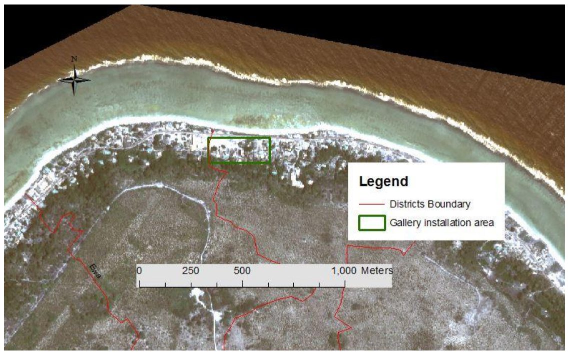

Fig. 4 – Range of positions for the installation of groundwater infiltration gallery (in green)

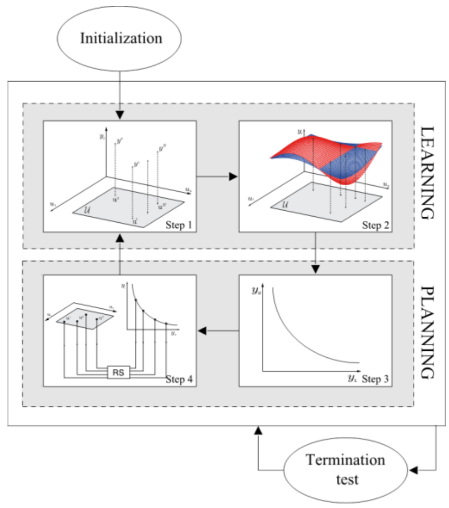

Fig.5 – Diagram of Global Interactive Response Surface procedure

Results and discussion

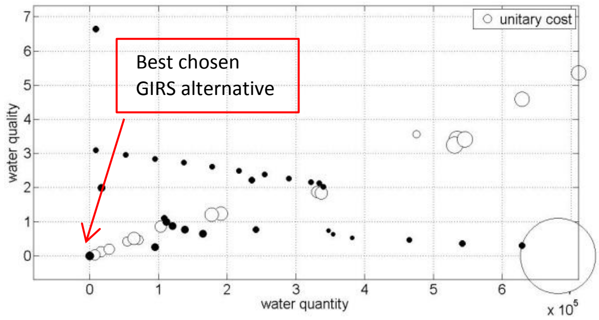

Fig. 6 - Performances of the alternatives obtained by the expert (white circles) and the GIRS methodology Pareto-efficient ones (black circles). Circle dimension represents cost objective.

GIRS methodology was applied with the goal of finding improved solutions at small additional computational cost with respect to those obtained via 'what-if' analysis by a field expert from Politecnico di Milano. The initial sample data set of input (decisions) and output (objectives) values was built using a subset of alternatives chosen with Latin Hypercube sampling technique.
Procedure was stopped at the third iteration as the variation of the hypervolume of the objective space dominated by the Pareto front from previous iteration was under a 2% chosen threshold (termination test).

The response surface of the three objectives was obtained using feedforward neural networks, obtaining good performances for the water quality objective (R^2=0.99), the water quantity objective (R^2=0.7) and the unitary cost objective (R^2=0.7), and more importantly, simulating with SEAWAT only the 0,5% of the overall alternative set. The performance of the Pareto-efficient solutions computed using GIRS approach and those obtained by the expert are reported in Figure 6. GIRS approach was able to single out more solutions than the expert, whose solutions are Pareto dominated, and moreover mostly concentrated in the compromise region of the Pareto-front (Figure 7) where generally solutions are not only efficient but also fairly balanced among the objectives.

Conclusions

In this paper the Global Interactive Response Surface (GIRS) approach combined with SEAWAT simulations, is adopted to optimally designing a horizontal gallery for controlling saltwater intrusion in the aquifer of Nauru. Results show that GIRS is able of obtaining a higher number of approximated Pareto-efficient solutions at small additional computational cost with respect to an expert running a 'what-if' analysis, also finding solutions better spread near minima of the objective indicators. Future research will explore the space for improvement by fully exploiting the potential of the GIRS methodology to emulate high-resource demanding models, also in other hydrogeological fields.

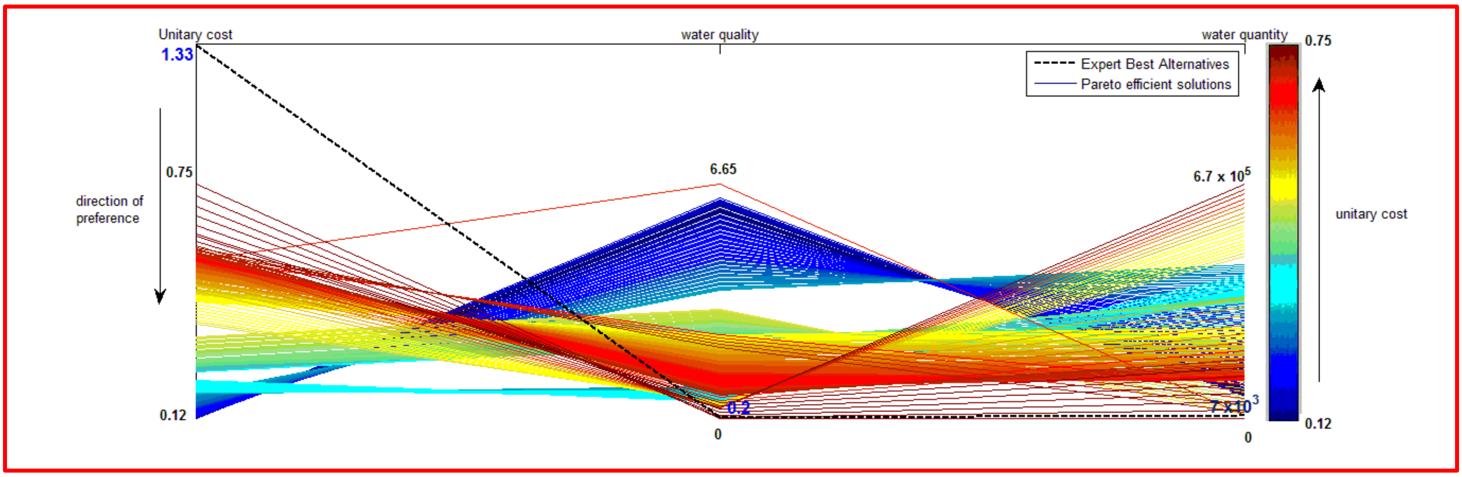

Fig.7 – Parallel plot of Pareto efficient solutions found by Global Interactive Response Surface at the last iteration. Best alternative chosen among those evaluated by expert is near to best GIRS chosen one for what concern quality and quantity objective , but highly far concerning cost objective. GIRS efficient solutions are more fairly distributed near the minimum of the objective values

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