Prospects and modern techniques for an optimal groundwater management

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Over-pumping in coastal regions causes intrusion of seawater into the coastal aquifers

Resulting in:
- lowering of the water table along the coastline
- reducing the available volume of groundwater reservoir
- deterioration of groundwater quality
• One of the management techniques to control the saltwater intrusion is to install injection wells and create an artificial barrier by raising the water table.

• Alternatively, the control of the pumping volume.
Keeping the **coastal water resources** in good quality for both the human communities and the environment.

The **goal** is to introduce an optimal pumping strategy in order to achieve:

- Adequacy of the fresh water to cover water demand
- Inhibition of the seawater intrusion front

**How this is going to be obtained??**
By introducing an optimal management strategy that will maximize the pumping rates without violating environmental constraints imposed in critical locations near the coast that are necessary to achieve quality standards.

However, the numerical simulation of the groundwater flow field that is necessary to simulate the aquifer enters a high computational cost that is getting even higher when an optimization procedure is required in order to achieve our goals.
1) Development of a groundwater flow simulation model of the coastal physical system (PTC Simulator)
   - Geophysical Characterization
   - Boundary Conditions

2) Development of a management model:  
   - Linear Programming (Simplex Method)
   - Heuristic Optimization (Differential Evolutionary Algorithm)
Calibrated Hydraulic Heads
Objective Function: the maximization of the total extracted fresh water volume from five pre-selected pumping locations

\[ \max \sum_{i=1}^{5} q_i \]

Subject to:

- \( h_j \geq 102.5 \) \( j = 1, \ldots, 10 \)
- Well 1: \( 0 \leq q_1 \leq 1800 \)
- Well 2: \( 0 \leq q_2 \leq 2520 \)
- Well 3: \( 0 \leq q_3 \leq 576 \)
- Well 4: \( 0 \leq q_4 \leq 2520 \)
- Well 5: \( 0 \leq q_5 \leq 146 \)
An **Evolutionary Algorithm (EA)** is a generic term used to indicate any population-based meta-heuristic optimization algorithm that uses mechanisms inspired by biological evolution, such as reproduction, mutation and recombination.

**Simplex Method** is a classical well established linear programming algorithm that under specific conditions can be applied to solve linearized problems.
Solution Methodology

1. An initial population of candidate solutions is created with uniform probability within the constrained space.

2. For each candidate solution (pumping scheme) the response of the physical model is calculated (hydraulic head field), using simulator.

3. The hydraulic head constraints are evaluated at the observation locations and the objective function is calculated for each candidate solution.

4. The next generation of solutions is generated considering the mechanisms of mutation and cross-over and they are evaluated (as in steps 2, 3).

5. Candidate solutions of the next generation are compared one by one to the corresponding solutions of the previous generation. The best of each pair survives the selection procedure.
### RESULTS - Physical System Response

<table>
<thead>
<tr>
<th>Well</th>
<th>Current Pumping (m³/day)</th>
<th>Optimal Solution (m³/day)</th>
<th>Optimal Solution (m³/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
<td>Operation Policy</td>
<td>Simplex Method</td>
<td>DE algorithm</td>
</tr>
<tr>
<td>q₁</td>
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<td>1800</td>
<td>1800</td>
</tr>
<tr>
<td>q₂</td>
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<tr>
<td>Σqᵢ</td>
<td>7562</td>
<td>4942.9</td>
<td>4935.7</td>
</tr>
</tbody>
</table>

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**Diagram:**
- Mediterranean Sea
- Seawater Intrusion Front
- Observation Locations

Scenarios:
- **Scenario 1:** Current Pumping Scheme
- **Scenario 2:** Optimal Pumping Scheme
2\textsuperscript{nd} Approach

1) The accurate groundwater flow \textit{simulation model} of the coastal physical system is replaced by an Artificial Neural Network (ANN) that serves as a fast approximation to the physical system under consideration.

2) Then a \textbf{Differential Evolution (DE)} algorithm is combined with the ANN to provide a tool for the fast testing of different optimal operational strategies for pumping wells.

How this is going to be obtained???
Initially, **successive calls** to the simulator for a wide range of pumping values, are used to provide the **training data** to the ANN.

Then, the ANN is used as an **approximation model** to the computational expensive simulation model, successively called by the DE algorithm to evaluate candidate solutions and **provide the optimal one** for the corresponding constraints.

The ANN, once trained, can be used for different optimization runs at a minimal computational cost without retraining.
The area of interest is placed in the **Northern part of Rhodes Island** in Greece and covers approximately **217km²**.

The extremely high water demand, especially during the summer period, is mainly covered by **pumping of subsurface water resources** at inland locations, where the water quality is still at high level.

The **aquifer depth** at the shoreline is 140m and goes up to 400m towards inland.
Objective Function ➔ Min

\[ f = f_1 + f_2 + f_3 \]

\[ f_1 = \frac{20000 - \sum_{i=1}^{5} Q_i}{10000} \]

\[ f_2 = \sum_{j=1}^{22} g_j \]

\[ f_3 = \begin{cases} 1 & \text{if } f_2 > 0 \\ 0 & \text{otherwise} \end{cases} \]

Constraints

\[ g_j = \begin{cases} \min_{water\_elev_j} - water\_elev_j & \text{if } water\_elev_j < \min_{water\_elev_j} \\ 0 & \text{otherwise} \end{cases} \]

- Term \( f_1 \) maximize the sum of the pumping rates
- Terms \( f_2 \) and \( f_3 \) become zero for all feasible solutions
Results

The ANN serves as a **fast approximation model** to the “precise” but computational expensive numerical model.

The ANN managed to provide **very satisfactory predictions** to the physical model, and the **error** between the NUMERICAL SIMULATOR calculations and the ANN predictions of the water table elevation remained in **acceptable for practical applications level**.
Rational management of the pumping activity in a coastal aquifer could significantly contribute in the inhibition of the seawater front.

Evolutionary Algorithms belong to a class of search methods with remarkable balance between exploitation of the best solutions and exploration of the search space that is necessary to achieve a almost global optimal solution.
The use of the ANN as an approximation model to the physical system allows for the **fast and easy testing of different scenarios** of constraints. This is actually the **main driving force for adopting the ANN** to replace the computational expensive groundwater numerical simulator.

As a result, **various strategies can be considered** and the trade-offs between maximization of pumping rates and the minimization of environmental effects can be considered in a more rational and systematic way.
References


