Numerical modelling and control of seawater intrusion in coastal aquifers

Modélisation numérique et contrôle des intrusions d’eau de mer dans les aquifères côtiers

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ABSTRACT: This paper presents the results of an investigation into numerical modelling and control of seawater intrusion. A coupled transient density-dependent finite element model has been used for modelling of seawater intrusion. Also, a new cost-effective method is presented for effective control of seawater intrusion in coastal aquifers. This methodology ADR (Abstraction, Desalination and Recharge) includes abstraction of saline water, desalination and recharge of a part of the excess desalinated water to the aquifer while the rest of the desalinated water can be used for domestic consumption. The simulation model has been integrated with an genetic algorithm (GA) to examine different scenarios to control seawater intrusion including different combinations of abstraction, desalination and recharge. The main objectives of the model are to minimize the total capital and operational costs of the abstraction and recharge wells and the salt concentrations in the aquifer. The results show that the proposed ADR system performs significantly better than using abstraction or recharge wells alone as it gives the least cost and least salinity in the aquifer.

RÉSUMÉ : Cet article présente les résultats d’une étude sur la modélisation numérique et le contrôle des intrusions d’eau de mer. Un couplage transitoire à densité variable par éléments finis a été utilisé pour modéliser les intrusions d’eau de mer. De plus, une nouvelle méthode est présentée pour un contrôle optimisé des intrusions d’eau salée. Cette méthodologie ADR (Abstraction, Desalination and Recharge) inclut l’extraction d’eau saline, le dessalement et la recharge dans l’aquifère d’une partie de l’excès d’eau dessalée tandis que le reste d’eau dessalée peut être utilisée pour un usage domestique. Le modèle de simulation a été intégré à l’aide d’un algorithme génétique (GA) dans le but d’examiner différents scénarios pour le contrôle des intrusions d’eau de mer incluant différentes combinaisons d’extraction, de dessalement, et de recharge. L’objectif principal du modèle est de minimiser le coût total et le nombre d’opérations pour l’extraction et la recharge des puits ainsi que la concentration en sel dans l’aquifère. Les résultats montrent que la méthode ADR proposée donne de biens meilleurs résultats que l’extraction et la recharge des puits seules du fait qu’elle conduit à un coût et une salinité dans l’aquifère minimaux.

KEYWORDS: numerical modelling, seawater intrusion, optimal management, abstraction, recharge

1 INTRODUCTION.

Seawater intrusion is a major problem threatening water resources in many parts of the world. The intrusion of saline water in groundwater is considered a special category of pollution, making groundwater resources unsuitable for human, industrial and irrigation uses. Mixing of 2-3% salinity would render the fresh groundwater resources unsuitable for human consumption. A 5% mixing of salinity with freshwater in an aquifer is enough to make the aquifer unsuitable for any use (Abd-Elhamid and Javadi, 2011). Seawater intrusion hence reduces the freshwater storage in coastal aquifers and in extreme cases can result in abandonment of freshwater supply wells. Remediation of groundwater could be very costly and could take a long time depending on the source and level of salinization. As a result, groundwater resources should be protected from saltwater intrusion, using suitable measures. To control saline intrusion, a seaward hydraulic gradient should be maintained and a proportion of the fresh-water should be allowed to flow into the sea. Risks of saline intrusion clearly limit the extent to which a coastal aquifer can be developed for water supply. The management of a coastal aquifer is concerned with deciding an acceptable ultimate landward extent of the saline water and calculating the appropriate discharge of freshwater necessary to maintain the seawater-fresh water interface in that position. A number of methods have been proposed to control seawater intrusion including: reduction of pumping rates, relocation of pumping wells, use of subsurface barriers, natural recharge, artificial recharge, abstraction of saline water and combination techniques (Todd, 1974). This study presents a cost-effective methodology to control seawater intrusion in coastal aquifers. This methodology (ADR - Abstraction, Desalination and Recharge) consists of three steps: abstraction of brackish water from the saline zone, desalination of the abstracted brackish water using reverse osmosis (RO) treatment process and recharge of the treated water into the aquifer.

Generally, the seawater intrusion is a highly nonlinear process. Spatial and temporal simulation of this process will require numerical methods such as the finite element method or finite difference method to solve the nonlinear governing equations of flow and solute transport through saturated/unsaturated porous media. Numerical simulation models can be used to examine a limited number of design options of these management methods, by trial and error (e.g. Mahesha, 1996 and Rastogi et al., 2004). However, optimization tools can be combined with simulation models to search for the optimal solution in a wide search space of design variables.

In recent years, a number of simulation models have been combined with optimization techniques to address groundwater management problems. The combined simulation and optimization model can identify an optimal management strategy by considering appropriate management objectives and constraints. The genetic algorithm (GA) optimization tool has the capability to deal with a wide range of optimization problems. These techniques have been applied by a number of researchers to coastal aquifer problems. Different simulation
models (or Meta models) have been integrated with GA to optimize different management schemes to limit seawater intrusion. These studies have generally focused on controlling progressive advancement of saline water, mainly in the two dimensional areal section. Maximization of the total pumping rate from wells, minimization of the total recharge rate into wells and minimization of the total amount of concentration in the aquifer are the major objective functions of these studies (e.g., Sreekanth and Datta, 2010; Dhar and Datta, 2009; EL-Ghandour et al., 2008; Eusuff and Lansey, 2004; Gordu et al., 2001 and Sreedevi and Venkuri, 1996).

This study presents the development of a coupled transient density-dependent finite element model for simulation of fluid flow and solute transport in soils and its application to simulate seawater intrusion in coastal aquifers. In order to effectively determine the optimal solution for control of seawater intrusion the simulation model is integrated with a GA optimization model to examine three scenarios: abstraction of brackish water, recharge of fresh water, and combination of abstraction, recharge and desalination (ADR). The objectives and constraints of these management scenarios include minimizing the capital and operation costs, minimizing salt concentrations in the aquifer, and determining the optimal depth, location, and abstraction/recharge rates of the wells.

2 SIMULATION-OPTIMIZATION METHODOLOGY

In this work, an in-house finite element model, (Saturated/Unsaturated Fluid flow and solute Transport - SUFT), has been used to study saltwater intrusion in coastal aquifers. The model uses a hybrid finite element and finite difference methods to solve density-dependent fluid flow and transport mass balance equations. The model can handle a wide range of real-world problems including the simulation of groundwater flow and solute transport separately and coupled fluid flow and solute transport, in addition to saltwater intrusion in coastal aquifers. It has been validated against a number of case studies from the literature. The details of mathematical formulation and numerical implementation of the model can be found in Abd-Elhamid and Javadi (2011). In addition, an optimization model based on a simple genetic algorithm (GA) was integrated with the simulation model to optimize the arrangements for control of seawater intrusion. The GA has been used, as a powerful search and optimization algorithm, in many fields of engineering. It consists of some procedures that search for solutions of complex optimization problems based on the Darwinian theory of “survival of the fittest” where the strongest offspring in a generation are more likely to survive and reproduce. In this technique an initial set of possible solutions (initial population) is randomly generated. Each member of the initial population is encoded as a chromosome with binary bit string. Cycles of evaluation, selection, crossover and mutation are repeated in an iterative process, where the population of chromosomes evolves to make a new generation in each cycle. The chromosomes for the optimal solution are the final outcome of these cycles (Sivanandam and Deepa, 2008).

In the developed simulation-optimization process, the GA repeatedly calls the SUFT model to compute state variables (pressure head and concentration) for different sets of generated design variables. After computing the objective function and evaluating its fitness, the processes of selection, crossover, and mutation are performed in the GA procedure to update the values of decision variables. The new values of decision variables are then returned to SUFT and the process is repeated until it satisfies optimal criteria or it reaches the maximum generation number.

3 APPLICATION

The simulation-optimization model was applied to one of the most popular benchmark problems in seawater intrusion in coastal aquifers, widely known as Henry’s saltwater intrusion problem. Henry’s problem involves seawater intrusion in a confined aquifer, subject to three different boundary conditions: constant recharge flux of freshwater on the left boundary, hydrostatic seawater pressure on the right boundary and impermeable boundaries along the top and bottom of aquifer as shown in Figure (1). The parameter values used for numerical simulations are summarized in Table (1). The aquifer domain is represented by 661 nodes and 200 quadrilateral isoparametric elements, each of size 10 m by 10 m. The domain considered is 100 m high and 200 m long. Freshwater concentrations (c=0) and natural steady-state pressures are set as the initial conditions everywhere in the aquifer. The problem is analyzed using the developed finite element model, and the results are compared with some results reported in the literature. The seawater wedge is chosen to be represented by 0.5 isochlor, which is an approach adopted by many researchers.

Rastogi et al. (2004) considered the dispersion coefficients to be velocity dependent under steady state conditions and selected values for longitudinal and transverse dispersivities as 0.5 and 0.1 m respectively. The same approach is used in the current work and the results are compared with a number of known solutions from the literature. Figure (2) shows these results in terms of the position of 0.5 iso-concentration lines.

Figure 1. Boundary conditions of Henry’s problem

Table 1. The parameters used in Henry’s problem

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_w$ : coefficient of water molecular diffusion [m$^2$/s]</td>
<td>$6.6*10^{-9}$</td>
</tr>
<tr>
<td>$Q_w$ : inland fresh water flux [m$^3$/sec]</td>
<td>$6.6*10^{-5}$</td>
</tr>
<tr>
<td>k : permeability [m$^2$]</td>
<td>$1.0*10^{-7}$</td>
</tr>
<tr>
<td>n : porosity [-]</td>
<td>0.35</td>
</tr>
<tr>
<td>g : gravitational acceleration [m/s$^2$]</td>
<td>9.8</td>
</tr>
<tr>
<td>$\rho_w$ : density of fresh water [kg/m$^3$]</td>
<td>1000</td>
</tr>
<tr>
<td>$\rho_s$ : density of sea water [kg/m$^3$]</td>
<td>1025</td>
</tr>
<tr>
<td>$\mu$ : fluid viscosity [kg / (m.s)]</td>
<td>0.001</td>
</tr>
<tr>
<td>$\alpha_t, \alpha_L$ : transverse and longitudinal dispersivity [m]</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Figure 2. 0.5 Isochlor lines for steady-state variable dispersion
4 FORMULATION OF MANAGEMENT MODELS

The developed simulation-optimization model was applied to the hypothetical aquifer in order to seek the optimal cost-effective strategy to control seawater intrusion. The aquifer was subjected to three management scenarios: abstraction of brackish water, recharge of fresh water, and combination of abstraction, recharge and desalination (ADR). The main objectives of these scenarios were to minimize the total construction and operation costs of management process and also to minimize the total concentration of salt in the aquifer. These multiple objective functions are represented mathematically using a single scalar objective function (Qahman et al., 2009 and Park and Aral, 2004) for each scenario as follows:

Management model 1 (Abstraction only)

\[
\min f = p_1 \cdot \left( \sum_{i=1}^{N} c_i \right) + p_2 \cdot Q_A \cdot (C_A + C_T) + p_3 \cdot D_A \cdot (C_{DW})
\]  

\( (1) \)

Management model 2 (Recharge only)

\[
\min f = p_1 \cdot \left( \sum_{i=1}^{N} c_i \right) + p_4 \cdot Q_R \cdot (C_{RW}) + p_5 \cdot D_R \cdot (C_{DW})
\]  

\( (2) \)

Management model 3 (Abstraction, Desalination and Recharge ADR)

\[
\min f = p_1 \cdot \left( \sum_{i=1}^{N} c_i \right) + p_2 \cdot Q_A \cdot (C_A + C_T) + p_3 \cdot D_A \cdot (C_{DW}) + p_4 \cdot Q_R \cdot (C_R) + p_5 \cdot D_R \cdot (C_{DW})
\]  

\( (3) \)

where

- \( f \) is the objective function in terms of the total cost.
- \( N \) is the total number of nodes in the domain.
- \( c \) is the total amount of solute mass in the aquifer (mg/l).
- \( p_1, p_2, p_3, p_4 \) and \( p_5 \) are the weighting parameters.
- \( D_A \) is the depth of abstraction well (m).
- \( Q_A \) is the abstraction rate (m³/sec).
- \( C_A \) is the cost of abstraction ($/m³).
- \( C_T \) is the cost of treatment ($/m³).
- \( C_{DW} \) is the cost of installation/drilling of well ($/m).
- \( Q_R \) is the recharge rate (m³/sec).
- \( D_R \) is the depth of recharge well (m).
- \( C_R \) is the cost of recharge ($/m³).
- \( C_{RW} \) is the price of water ($/m³).

In the first scenario the effect of continuous abstraction of brackish water from the well was considered. This model has three decision variables: location, depth and rate of abstraction. In the second scenario the aquifer was subject to artificial recharge of freshwater into a well as the strategy to increase the hydraulic gradient of groundwater toward the sea. Location, depth, and recharge rate are considered as the decision variables to be optimized to reduce the total cost. The third management scenario was developed by combining management models 1 and 2 to prevent/control seawater intrusion. Locations, depths, and abstraction/recharge seawater rates of the abstraction and recharge wells are considered as decision variables. Figure (3) shows the decision variables considered in the simulation-optimization model. Based on the available decision variables in each scenario, the management objectives are achieved within a set of constraints including side constraints for well depths, well locations and abstraction/recharge rates as:

- \( 0.0 < Q_{A,R} \text{ (m³/sec)} < 0.1 \),
- \( 0.0 < L_{A,R} \text{ (m)} < 200.0 \) and
- \( 0.0 < D_{A,R} \text{ (m)} < 100.0 \).

In these management models the costs are considered based on the available data from literature. According to the literature these costs are considered as (Qahman and Larabi, 2006):

- cost of installation/drilling of well per unit depth: US$1000,
- cost of abstraction per cubic meter: US$0.42,
- cost of recharge per cubic meter: US$0.48,
- cost of treatment (desalination) per cubic meter: US$0.6
- price of water per cubic meter: US$1.5.

The GA parameters used are: population size = 100, probability of crossover = 0.7, and probability of mutation = 0.03. Typical CPU time used for 100 generations is about 3 h on an Intel Core i7 8 at 2.8GHz with 8GB RAM.

5 RESULTS AND DISCUSSION

The results obtained from the simulation-optimization process for all management scenarios in terms of the optimal depth, location and rate of the abstraction/recharge well with the corresponding total costs are summarized in Table (2). The total cost required to control seawater intrusion using the first management model is determined as $2.62 million per year. The optimal depth is 90m, the optimal location is 50m from the seashore, and the optimal abstraction rate is 0.083 m³/s, while the total concentration has reduced from 167 to 149 mg/l. In the second management scenario, the total cost is $5.72 million per year, the optimal depth is 60 m, the optimal location is 90m from the seashore, and the optimal abstraction rate is 0.095 m³/s, while the total concentration in the aquifer is reduced from 167 to 149 mg/l. Using management model 3, the total cost is $1.32 million per year. The optimal depths for abstraction and recharge wells are 90m and 80m, respectively; the optimal locations for abstraction and recharge wells are 50m and 110m from the seashore, and the optimal rates for abstraction and recharge wells are 0.018 m³/s and 0.048 m³/s, respectively. The total concentration in the aquifer is reduced from 167 mg/l to 142 mg/l.

Although, all three management models reversed seawater intrusion into the coastal aquifer and moved the transition zone between the seawater and freshwater toward the sea, the third
management model is the most cost effective strategy to control the seawater intrusion in this hypothetical aquifer. The cost of this model is about 50% of the abstraction only scenario and 25% of the recharge scenario. The reason for this lowest cost is partly because the cost associated with the supply of water used for recharge does not apply in this case as the required water is provided primarily from the treatment of the abstracted saline water. In addition, the excess treated water can be directly used for other purposes. The other aspect of efficiency of this model is about minimization of total concentration of salinity in the aquifer as it reduced the total concentration in the system by 15%, while the first and second scenarios reduced it by 10-11%. Figure (4) clearly shows the capability of third model in controlling the further advance of the freshwater/seawater interface in comparison with other models.

Table 2. Summary of the results obtained from the simulation-optimization models for the hypothetical case study.

<table>
<thead>
<tr>
<th>Model</th>
<th>L (m)</th>
<th>D (m)</th>
<th>Q (m³/sec)</th>
<th>Total C</th>
<th>Cost ($/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Management</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>167</td>
<td>-</td>
</tr>
<tr>
<td>Abstraction only</td>
<td>50</td>
<td>90</td>
<td>-0.083</td>
<td>149</td>
<td>2.62E+6</td>
</tr>
<tr>
<td>Recharge only</td>
<td>90</td>
<td>60</td>
<td>0.095</td>
<td>151</td>
<td>5.72E+6</td>
</tr>
<tr>
<td>Abstraction and Recharge</td>
<td>50</td>
<td>90</td>
<td>-0.048</td>
<td>142</td>
<td>1.32E+6</td>
</tr>
</tbody>
</table>

Figure 4. 0.5 isochlors from simulation-optimization models for the hypothetical case.

6 CONCLUSIONS

This paper presented the development and application of a simulation-optimization model to control seawater intrusion in coastal aquifers. A coupled transient density-dependent finite element model was used to simulate the seawater intrusion problem. This simulation model was linked with a genetic algorithm to optimize control arrangements for a hypothetical aquifer using three management scenarios: abstraction of brackish water, recharge of fresh water, and combination of abstraction and recharge. The efficiencies of the proposed management scenarios in controlling seawater intrusion in terms of both the solute concentration in the aquifer and the total costs (of construction and operation) of the management policy were evaluated using this integrated model. The optimal locations, depths, and rates of abstraction and/or recharge wells in each scenario were determined. The results show that all three scenarios could be effective in controlling sea intrusion but using model 3 (a combination of abstraction and recharge wells) resulted in the least cost and salt concentration in aquifers and maximum movement of freshwater/saline water interface towards the sea. The results also show that for the case study considered in this paper, the amount of abstracted and treated water is three times the amount required for recharge; therefore, the remaining treated water can be used directly for different purposes. Finally, ADR is an effective tool to control seawater intrusion and can be applied in areas where there is a risk of seawater intrusion.

7 REFERENCES


