A simulation-optimization model to study the control of seawater intrusion in coastal aquifers using ADR methodology

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ABSTRACT

Seawater intrusion represents a challenging problem in coastal regions as it poses a major limitation to utilization of groundwater in these areas. Seawater intrusion is one of the most important environmental problems that degrade groundwater resources. Therefore, saltwater intrusion should be controlled to protect groundwater resources. This paper presents development and application of a simulation-optimization model to control seawater intrusion in coastal aquifers. A coupled transient density-dependent finite element model is developed for simulation of fluid flow and solute transport and used to simulate seawater intrusion. A simulation-optimization model is also developed to study the control of seawater intrusion in coastal aquifers using three management models; abstraction of brackish water, recharge of fresh water and combination of abstraction and recharge. The main objective of the models is to minimize the construction and operation costs by identifying the optimal depth, location and abstraction/recharge rates for abstraction and/or recharge wells. A new methodology ADR is presented to control seawater intrusion by abstracting brackish water, desalinating it using reverse osmosis and recharging to the aquifer. The efficiencies of the proposed management scenarios have been examined and compared. The results show that all the three scenarios could be effective in controlling sea intrusion but using ADR methodology results in the lowest cost and salt concentration in aquifers and maximum movement of freshwater/saline water interface towards the sea. The developed model is an effective tool to control seawater intrusion in coastal aquifers and can be applied in areas where there is a risk of seawater intrusion.

Keywords: *seawater intrusion, control, finite element, GA, simulation-optimization, ADR.*

INTRODUCTION

Seawater intrusion increases salt concentration in groundwater which places limitations on its uses. Therefore, efficient control of seawater intrusion is very important to protect groundwater resources from depletion. Todd (1974) discussed various means of preventing saltwater including: reduction of the abstraction rates, relocation of abstraction wells, subsurface barriers, natural recharge, artificial recharge, abstraction of saline water, and combination of some of these systems. Numerical simulation models can be used to examine a limited number of design options by trial and error. However, optimization methods can be combined with simulation models to search for the optimal solution in a wide search space of design variables. The motivation for the development of the simulation-optimization (S/O) approach for the control of seawater intrusion is the enormous cost of groundwater remediation. The S/O approach can be used efficiently in groundwater remediation system design and also in other groundwater quality management problems. Development and application of optimization techniques in association with seawater intrusion was presented by a number of researchers (e.g. Cheng *et al*. 2000, Datta 2000 and Bhattacharjya and Datta 2005). Only a limited number of studies have concentrated on the problems of seawater intrusion control. To the authors' knowledge, no attempt has been made in the literature to develop or use a S/O model to study optimal control of seawater intrusion using a combination of abstraction and recharge wells. The only related work in the literature appears to be that of Rastogi *et al* (2004) who used a simulation model to study the effect of abstraction and recharge on the intrusion of seawater by trial-and-error. To date, no work has been done on reduction of costs of construction and operation of such systems. This paper presents the development and application of a S/O model to control seawater intrusion in coastal aquifers. A simulation model is integrated with a genetic algorithm (GA) optimization model to study the control of seawater intrusion in coastal aquifers using three management scenarios; abstraction of brackish water, recharge of fresh water and combination of abstraction and recharge. The objectives of these management scenarios include minimizing the total construction and operation cost, minimizing salt concentrations in the aquifer and determining the optimal depth, location and abstraction/recharge rates. The developed model is applied to a hypothetical case (Henry's problem). The efficiencies of the three management scenarios are examined and compared.

DEVELOPMENT OF A SIMULATION-OPTIMIZATION MODEL

The simulation-optimization model developed in this work is based on the integration of a GA with a coupled transient density-dependent FE model for flow and solute transport. In the developed S/O framework, the simulation model is repeatedly called by the GA to calculate the response of the system to each set of design variables generated by the GA. The simulation model is used to compute heads and salt concentrations for every node in the domain. These values are returned to the GA routine and used to evaluate the objective function value and determine the fitness of the solution in competition with other generated solutions. The coupling of fluid flow and solute transport in unsaturated soil is modeled using two sets of equations. The first set of equations describes water flow and air flow and the second set describes solute transport. The nonlinear governing differential equations of fluid flow and solute transport, considering density-dependent flow, are solved using the finite element method in the space domain and a finite difference scheme in the time domain. The flow and transport equations are coupled through Darcy's law and a constitutive equation relating fluid density to salt concentration $\rho = \rho_f (1 + \varepsilon C)$. The numerical solution of coupled fluid flow and solute transport with appropriate boundary and initial conditions leads to the computation of pore water and air pressures at all nodes. The pressure head, fluid velocity and fluid density are then calculated. The calculated velocities are used to define the dispersion coefficient for the solute transport equation. The solute transport equation is then solved for concentrations at every node in the domain and this process is repeated at every time step. A GA-based optimization approach is used in this work to incorporate a simulation model within an optimization-based management model to evolve an optimal management strategy. Three management models are developed in this work to control seawater intrusion in coastal aquifers; abstraction of brackish water, recharge of fresh water and combination between abstraction and recharge. The main objective of the S/O model is to minimize the construction and operation costs by identifying the optimal depth, location and abstraction/recharge rates for abstraction and/or recharge wells to control the intrusion of seawater.

APPLICATION OF THE S/O MODEL TO CONTROL SEAWATER INTRUSION

The developed S/O model is applied to control seawater intrusion in a hypothetical coastal aquifer, known as Henry's problem (Henry, 1964). The dimensions of the aquifer are assumed to be 200 m (length) and 100 m (thickness).The finite element mesh consists of 661 nodes and 200 elements, each of size 10.0 m by 10.0 m. The same parameters and initial and boundary conditions used by (Rsaogi, 2004) are used in this work. The application of the proposed S/O model to the current case has been done in two steps. The first step, the simulation model is applied with the initial and boundary conditions to compute pressure head and salt concentration at every node in the interred domain. The second step, the optimization model is applied to determine the decision variables; well depth, location and abstraction/recharge rates. The objective function for the three models is to minimize the total cost associated with well locations, depths and abstraction/recharge rates and treatment. Figure 1 shows the 0.5 isochlors for the three management models. Comparison between total costs, salt concentration in the aquifer and abstraction/recharge rates for the three management models are presented in Figure 2.

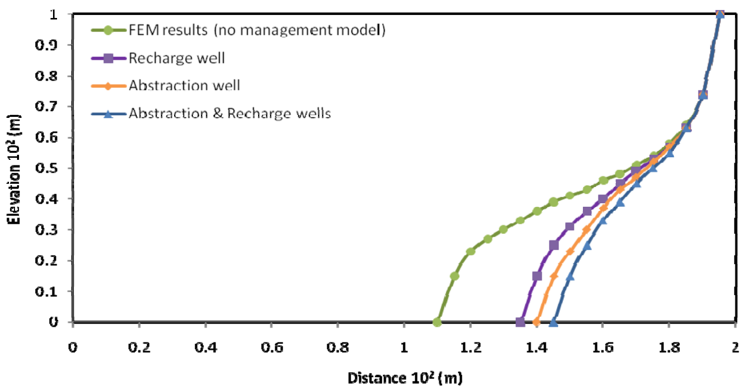
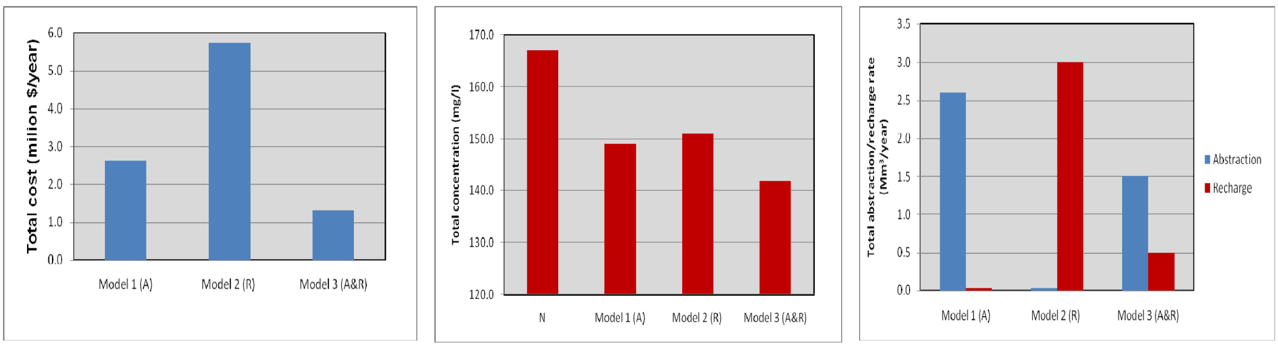


Figure 1. 0.5 isochlor distribution from S/O models for the hypothetical case



(a) *(b)* *(c)*

Figure 2. Comparison between the results of model 1, 2 and 3 for: (a) total costs, (b) total salt concentrations in the aquifer (c) and total abstraction/recharge rates

From these figures it can be concluded that: using recharge wells alone has reduced the total salt concentration in the aquifer from 167 where no management model is used (N) to 151(mg/l) through recharging 3 (Mm^3/year) of fresh water at a cost of $5.72 million/year. Using abstraction wells alone reduced the salt concentration to 149 (mg/l) through abstracting 2.6 (Mm^3/year) of saline water at cost of $2.62 million per year. However, using a combination of abstraction, and recharge (ADR) reduced salt concentration to 142 (mg/l) through abstraction of 1.5 (Mm^3/year) of saline water and recharge of 0.5 (Mm^3/year) with cost of $1.32 million/year.

CONCLUSIONS

This paper presents the development and application of a S/O model to control seawater intrusion in coastal aquifers using three management scenarios. The developed S/O model was applied to evaluate the three management scenarios to control seawater intrusion in coastal aquifers and to determine the optimal location, depth and rates of abstraction and/or recharge wells while minimizing the construction and operation costs. The efficiencies of the proposed management scenarios have been examined and compared. The results show that all the three scenarios could be effective in controlling seawater intrusion but using ADR in model 3 results in the lowest cost and salt concentration in aquifers and maximum movement of transition zone 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 proposes. The ADR appears to be more efficient and more practical, since it is a cost-effective method to control seawater intrusion in coastal aquifers. It can also be used for sustainable development of water resources in coastal areas where it provides a new source of water coming from treated water.

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