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Optimal control of seawater intrusion in coastal aquifers

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Abstract

Seawater intrusion is one of the most serious environmental problems in many coastal regions all over the world. This is because mixing a small quantity of seawater with groundwater makes it unsuitable for use and can result in abandonment of aquifers. Therefore, seawater intrusion should be prevented or at least controlled to protect groundwater resources. This paper presents a new method for optimal control of seawater intrusion. The proposed method is based on a combination of abstraction of saline water near shoreline and recharge of aquifer using surface ponds. The source of water for the surface pond could be treated waste water or excess of desalinated brackish water (if any), etc. The variable density flow and solute transport model, SUTRA, is integrated with a Genetic Algorithm optimization tool in order to investigate the efficacy of different scenarios of the seawater intrusion control in an unconfined costal aquifer. The locations of the pond and the abstraction well in relation to the shoreline, depth of abstraction well and the rates of abstraction and recharge are considered as the main decision variables of the optimization model, which aims to minimize the costs of construction and operation of the abstraction wells and recharge ponds as well as the salt concentrations in the aquifer. Comparison is made between the results of the proposed method and other methods of seawater intrusion control. The results indicate that the proposed method is efficient in controlling seawater intrusion. This proposed strategy can be considered as a powerful tool for cost-effective management of seawater intrusion in coastal aquifers.

Keywords: Numerical modelling, seawater intrusion, optimal management, abstraction, recharge

1. Introduction

Over 70% of the world's populations live in coastal areas. Overexploitation of groundwater abstraction to meet domestic and irrigation demands often leads to further encroachment of seawater interface into aquifer. The extent of this saltwater intrusion is the main source of deterioration of the groundwater quality in coastal areas. Therefore, finding methods for controlling this dynamic imbalance between freshwater and saline water has become a point of concern of modern times. A number of methods have been proposed to control this problem such as: reduction of pumping rates, use of subsurface barriers, artificial recharge and/or combination of these techniques. Numerical simulation models can be used to examine a limited number of design options of these management methods, by trial and error. 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 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 horizontal sections. Maximization of the total pumping rate from wells, minimization the total recharge rate into wells and minimization the total amount of concentration in the aquifer are the major objective functions of these studies [e.g., 1-10].

The focus of this paper is on development and application of a simulation–optimization technique to assess the efficiencies of a new management method to control of seawater intrusion in unconfined aquifers. This management model consists of application of artificial recharge by treated waste water through a designed pond above the aquifer. This methodology is an extension of the method proposed by Javadi et al.[1] who applied a combination of abstraction of saline water from the intrusion wedge, desalination and recharge of excess of desalinated water or treated waste water, into the aquifer. They showed that this method is an effective and economic method for controlling seawater intrusion. However, the main feature which makes a present study different from their work is that in the present work, artificial pits or ponds are used to collect the treated wastewater and recharge the aquifer. In this method, the collected

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water is allowed to percolate through the unsaturated zone to the underlying aquifer. The effect of ponded water on quality of water in aquifer was also studied by Eusuff and Lansey [8] with no reference to seawater intrusion control. They linked shuffled complex evolution algorithm (SCE) as the optimization tool with MODFLOW, MT3D, and MODPATH as finite difference simulation codes. In present study a genetic algorithm is integrated with the SUTRA (Saturated-Unsaturated TRAansport) flow and solute transport model to assess management scenarios to control seawater intrusion: abstraction of brackish water and combined 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 rates of abstraction/recharge features.

2. Simulation-Optimization methodology

In the current work a simulation model (SUTRA) was integrated with a GA to identify the optimal arrangements for the proposed seawater control method. A numerical model was developed for simulation of seawater intrusion process in coastal aquifer using SUTRA version (2.2). SUTRA implements a hybridization of finite element and integrated finite difference methods to solve the density dependent flow and transport mass balance equations; the finite element method is used for the spatial discretization and finite-difference approximation for the temporal discretization[11]. The general form of fluid flow and solute transport governing equations is presented in appendix.

On the other hand the optimization model was developed using a simple genetic algorithm. The GA is used, as a powerful search and optimization algorithm, in many fields of engineering as alternative for conventional optimization techniques. It consists of some procedures that search for solutions of complex problems based on the Darwinian theory of "survival of the fittest"[12] 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 selection, crossover and mutation are the other steps of this algorithm, where the population of chromosomes evolves through these steps to make a new generation in each cycle. The chromosomes with optimal solution are the final result of these cycles.

In the developed simulation-optimization process, the GA repeatedly calls SUTRA to compute state variables (pressure and concentration) as response to each set of generated design variables. After computing the objective function and evaluating its fitness, the processes of selection, crossover, and mutation are performed in a GA procedure to update the values of decision variables. The new values of decision variables are then returned to SUTRA 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 widely used benchmark problems in study of seawater intrusion, Henry's problem. Henry's problem involves seawater intrusion within 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 [11]. However for the purpose of this study the top boundary was modified to include the effect of artificial recharge in an unconfined aquifer. The idealized aquifer for the modified Henry's problem is shown in Figure 1. The parameter values used for numerical simulations are summarized in Table 1 according to Hughes and Sanford [13]. The domain is 200 m in length and 100 m in height. The domain was discretized using 200 elements (each of size 10m*10m) and 231 nodes. The initial concentration (C_o) within the model domain was set to zero. The system essentially reaches a steady state after 400 time steps, with time step of 100 minutes. Iso-concentration lines of salinity distribution under the above conditions (without any recharge and discharge source) at steady state condition are shown in Figure 2a. Figure 2b illustrates the steady state variations of flow velocity through the system. The total calculated mass of solute in the aquifer is 106 tons.

Dm	: coefficient of water molecular diffusion [m^2 /s]	$18.8571*10^{-4}$
Qin	: inland fresh water flux [m^3/s]	$6.6*10^{-5}$
k	: permeability [m^2]	$1.02041 *10^{-9}$
$\partial\rho/\partial C$	: change of fluid density with concentration [kg^2(seawater)/kg(dissolved solids). m^3]	700
ε	: porosity [dimensionless]	0.35
g	: gravitational acceleration [m /s^2]	9.8
Csea	: solute mass fraction of seawater [kg(dissolved solids)/kg(seawater)]	0.0357
ρsea	: density of sea water [kg/m^3]	1024.99
ρo	: density of fresh water [kg/m^2]	1000
μ	: fluid viscosity [kg/(m.s)]	0.001
αT, αL	: transverse and longitudinal dispersivity [m]	0.0

Table 1: The parameters used in Henry's problem

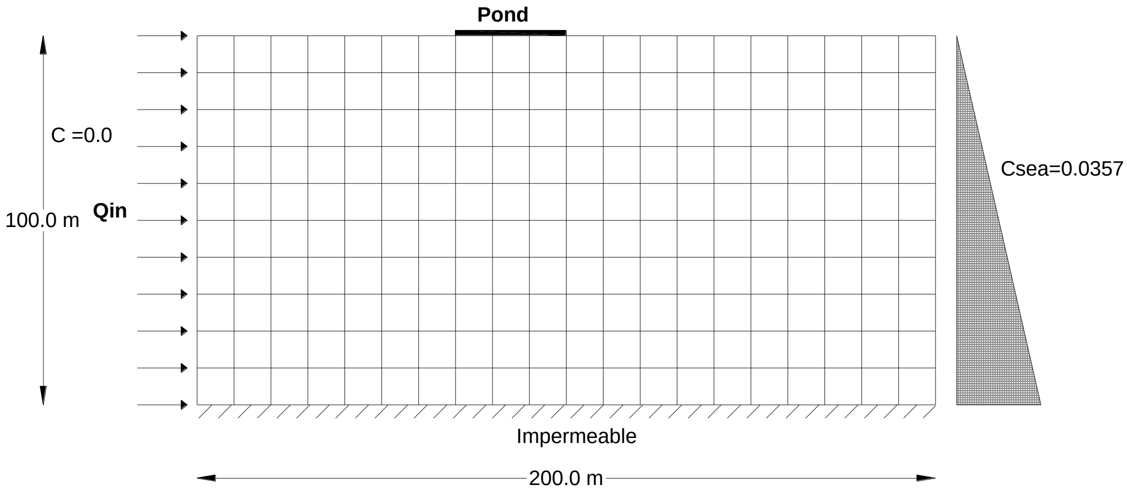
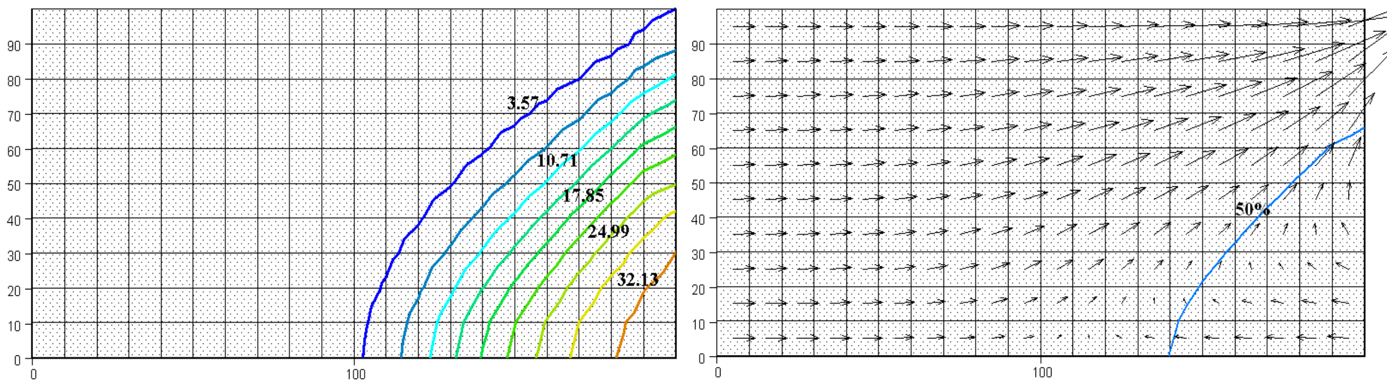


Figure 1: Boundary conditions of modified Henry's problem



(a) concentration distribution (kg/m^3) (b)flow velocity vector

Figure 2: Variation of concentration and velocity throughout the system in steady state condition

4. Formulation of management models

The developed simulation-optimization model was applied to the hypothetical unconfined aquifer in order to seek optimal cost-effective strategy to control seawater intrusion. The aquifer was subjected to two separate management scenarios: in the first scenario the effect of continuous abstraction of water from the well was considered whereas in the second scenario, the aquifer was subjected to both abstraction and artificial recharge through the surface pond. 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. The construction costs include installation and drilling costs, while the operation costs include abstraction, recharge and treatment costs. A single scalar objective function approach was used to optimize these multiple objective functions [1, 3, 5, 14].

In first scenario (Abstraction only) the cost function has direct relationship to the optimal rate of pumping and the location and depth of the abstraction well. Therefore, as shown in Figure 3, the model has mainly three decision variables: location, depth and rate of abstraction and the state variables are fluid pressure and salt concentrations that are calculated by SUTRA in every node in the domain. The objective function of this scenario can be represented mathematically as follows:

$$\min f = P_1 * \sum_{i=1}^{N} C_i + P_2 * QA * (CA + CT) + P_3 * DA * (CD) \tag{1}$$

where:

f : management objective function
N: total number of nodes in the domain
C_i: is the solute mass fraction at node i
QA: abstraction rate (m^3/sec)
DA: depth of abstraction well (m)
P_1,P_2 and P_3 : weighting parameters
CA: cost of abstraction ($/m^3)
CT: cost of treatment ($/m^3)
CD: cost of installation/drilling of well ($/m)

The total cost of this model consists of cost of installation/drilling of well per unit depth: $1000, cost of abstraction per cubic meter: $0.42, and cost of treatment per cubic meter: $0.6 [1]. The side constraints of the design variables in this case were:

$$0.0 < QA\ (m^3/s) < 0.1 \quad (2)$$
$$0.0 < LA\ (m) < 200.0 \quad (3)$$
$$0.0 < DA\ (m) < 100.0 \quad (4)$$

The second scenario is based on continuous abstraction of brackish water near the coast, desalination of the abstracted brakish water (e.g., using reverse osmosis) and reusing excess of this treated water (or treated waste water) as source of artificial recharge in the surface pond while the rest of the desalinated water is used to meet part of the demand for water. Generally, in natural state, infiltration of treated recharge water into aquifer is followed by the increase in the hydraulic gradient of the freshwater towards the sea. Consequently, it prevents the future advancement of saline water. In this model it is assumed that recharge water has been fully treated (c=0.0).In addition to the abstraction well variables of scenario 1, two recharge pond decision variables are also considered in the optimization: the pond location and the total recharge rate. The final objective function of this model is:

$$\min f = P_1 * \sum_{i=1}^{N} C_i + P_2 * QA * (CA + CT) + P_3 * DA * (CD) + P_4 * QR * (CR) + CP \quad (5)$$

where:

f : management objective function

QR: recharge rate (m^3/sec)

P_4: weighting parameters

CR: cost of recharge (\$/m^3)

CP: cost of pond construction (\$)

In this scenario the cost of pond construction and recharge operation were added to the objective function. Although for the purpose of this study the cost of pond construction was not considered in the calculation, it should be added to the total cost, based on design properties of pond, in real case studies. In addition to the side constraints detailed in equations 2-4, the following side constraints were considered for the recharge pond:

$$0.0 < QR\ (m^3/s) < 0.1 \quad (6)$$
$$0.0 < LR\ (m) < 160.0 \quad (7)$$

In both management models the GA uses the following parameters to randomly generate decision variables: population size = 100, total number of generations=200, probability of crossover = 0.7, and probability of mutation = 0.03. The average time required for simulation-optimization using an Intel(R) core(TM)2 Duo PC with CPU @2.00 GHZ(2 CPU) with 3.574 GB RAM was 2.5hours.

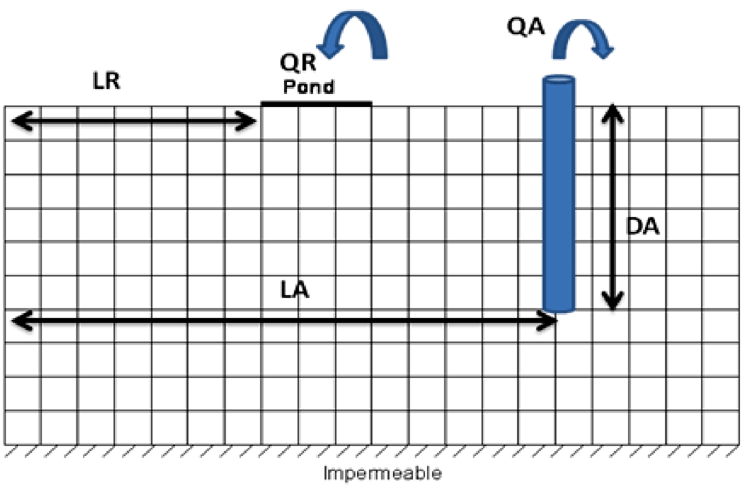


Figure 3: Schematic sketch for available decision variables

5. Results and discussion

The simulation-optimization model was used to determine the optimal arrangements in the two scenarios considered. The results obtained from this process for both management scenarios in terms of the optimal depth and location of the abstraction well, optimal location of the recharge pond, and optimal rates of abstraction and recharge together with the corresponding total costs are summarized in Table 2. The final concentration distributions for these models are shown in Figure 4 in the form of 50% isochlors.

The optimization of the first model (abstraction only), as defined in equation 1, yields the minimum total construction and operation costs to control seawater intrusion. The optimal depth is 80 m, the optimal location is 190m from the left boundary, and the optimal abstraction rate is 0.0745 m^3/s. This optimal arrangement requires $2.48 million per year as minimum cost. However, the total mass of salt in the aquifer is reduced from 106 tons to 78 tons.

The second management scenario seeks to minimize the total construction and operation costs, using both abstraction well and recharge pond, to control seawater intrusion. The total cost of this model based on relevant objective function (equation 5) is $0.652 million per year (without pond construction costs). The optimal depth for abstraction well is 90m, the optimal locations for abstraction well and recharge pond are 190m and 110m from the left boundary and the optimal rates for abstraction and recharge are 0.0144 and 0.0065 m^3/s, respectively. The total amount of salt in the aquifer is reduced from 106 tons to 37 tons.

The result shows that the second management model is more efficient and cost effective in reducing the salinity and controlling the seawater intrusion in the unconfined aquifer. The cost of this model (without pond construction cost) will be about a quarter of that of the first model. The other aspect of efficiency of this model is about minimization of total concentration of solute in the aquifer as it reduced the total mass of salt in system by 65%, while the first scenario reduced it by 26%.

Generally, the second management model appears to be very efficient and more practical, as it requires substantially lower cost and leads to further advancement of the freshwater/seawater interface toward the sea and lower concentration of salt in the aquifer as shown in Figure 4. In real case studies, it would be preferable to use other sources of water, such as treated wastewater, as the source of recharge for the pond and the desalinated brackish water can be used to meet the demand for potable water.

Model	L (m)	D (m)	Q (m^3/sec)	Total C (tons)	Cost ($/year)
No Management		-		106	-
Abstraction only	190	80	0.0745	78	$2.48*10^6$
Abstraction & Recharge	190 110	90 -	0.0144 0.0065	37	$0.652*10^6$ + CP*

*CP= Cost of Pond Construction

Table 2: Summary of the results obtained from the simulation – optimization models

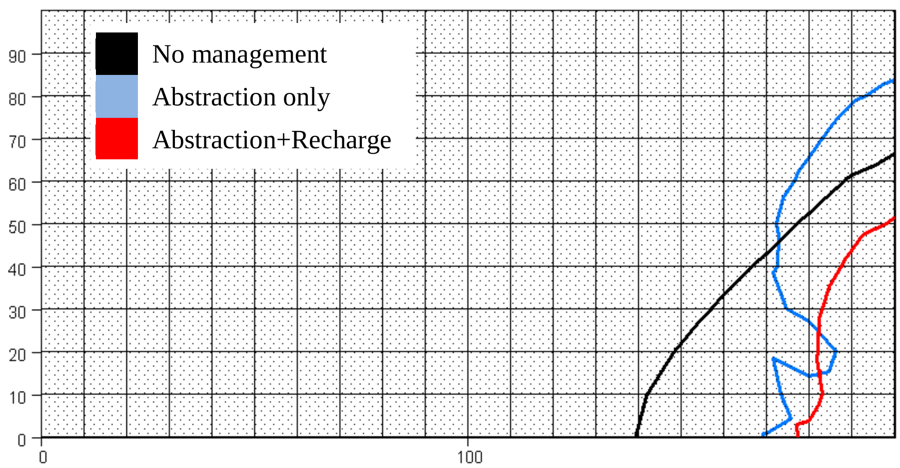


Figure 4: The 50% isochlors for optimal management solutions obtained from the simulation−optimization models

6. Summary and conclusion

This paper demonstrated the development and application of a new method to control seawater intrusion and a simulation-optimization model that can be used to optimize the arrangements in the proposed control methodology. The SUTRA code as simulation model was linked with a genetic algorithm to optimize control arrangements for a hypothetical unconfined aquifer. For the purpose of this study two different management scenarios were considered for the aquifer. The first scenario involved the use of abstraction well to control seawater intrusion whereas in the second scenario the combination of abstraction and artificial surface recharge was used as the strategy to control seawater intrusion.

The objective functions of these scenarios were to minimize the total cost of construction and operation of the management processes and to minimize the total amount of salt in the aquifer based on optimal locations of abstraction well and recharge pond, optimal depth of the abstraction well and the optimal rates of recharge/abstraction. The results show that the combination of abstraction well and artificial recharge pond resulted in the least cost and salt concentration in the aquifer and maximum movement of freshwater/saline water interface towards the sea. However this scenario showed that, for the case study considered, more than 50% of the desalinated water will be reused as recharge water. Considering the cost of desalination, it would be preferable (and even more cost-effective) to compensate this amount by recharging the aquifer using the treated wastewater in real case studies and use the desalinated water for domestic uses.

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Appendix: Governing equations

The SUTRA employs hybrid finite-element and integrated-finite-difference method to approximate the governing equations that describe the variable-density ground-water flow and solute transport processes in aquifer system within saturated-unsaturated conditions. Consequently, conservation of mass of fluid and conservation of mass of solute are the main equations that responsible for these processes respectively, [11]. The general forms of these equations summarized below:

Fluid mass balance equation:

$$\left(S_w \rho\, S_{op} + \varepsilon\, \rho \frac{\partial S_w}{\partial P}\right)\frac{\partial P}{\partial t} + \left(\varepsilon\, S_w \frac{\partial \rho}{\partial C}\right)\frac{\partial C}{\partial t} - \underline{\nabla}.\left[\left(\frac{\underline{\underline{k}}\, k_r\, \rho}{\mu}\right).\left(\underline{\nabla} P - \rho\, \underline{g}\right)\right] = Q_P$$

Solute mass balance equation:

$$\frac{\partial(\varepsilon\, S_w\, \rho\, C)}{\partial t} + \frac{\partial[(1-\varepsilon)\rho_s\, C_S]}{\partial t} = -\underline{\nabla}.\left(\varepsilon\, S_w\, \rho\, \underline{v}\, C\right) + \underline{\nabla}.\left[\varepsilon\ S_w\ \rho(D_m\, \underline{\underline{I}} + \underline{\underline{D}}).\underline{\nabla} C\right] + \varepsilon\, S_w\, \rho\, \Gamma_w + (1-\varepsilon)\rho_s\, \Gamma_S + Q_p C^*$$

where:

S_w : water saturation [dimensionless]

ρ : fluid density $[M/L^3]$

ε : porosity [dimensionless]

ρ_s : density of solid grains in solid matrix$[M/L^3]$

P : fluid pressure $[M/(L.T^2)]$

t :time [T]

C : solute mass fraction in fluid $[M_s/M]$

C* :solute concentration of fluid sources $[M_s/M]$

$\underline{\nabla}$: divergence of vector

$\underline{\underline{k}}$: solid matrix permeability $[L^2]$

k_r : relative permeability to fluid flow [dimensionless]

μ : fluid viscosity [M/(L.T)]

$\underline{g}$: gravity vector $[L/T^2]$

Q_p : fluid mass source $[M/(L^3.T)]$

$\underline{\underline{I}}$: identity tensor [dimensionless]

$\underline{\underline{D}}$: dispersion tensor $[L^2/T]$

C_s : specific concentration of adsorbate on solid grains $[M_s/M_G]$

$\underline{v}$: vector with components in i, j, and k directions [L/T]

Γ_w : solute mass source in fluid due to production reactions $[M_s/(M_G.T)]$

Γ_s : adsorbate mass source due to production reactions within adsorbed material itself $[M_s/(M.T)]$

D_m : apparent molecular diffusivity of solute in solution in a porous medium including tortuosity effects $[L^2/T]$

S_{op} : specific pressure storativity $[M_f/(L.T^2)]^{-1}$; $S_{op} = [(1-\varepsilon)\alpha + \varepsilon\beta]$
α and β are porous matrix and fluid compressibility respectively $[M/(L.T^2)]^{-1}$