Cost-Effective Management of Sea Water Intrusion in Shallow Unconfined Aquifers

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ABSTRACT

The cost efficiency aspects of different hydraulic barriers to control seawater intrusion (SWI) in shallow unconfined aquifer are investigated using the direct integration of simulation model with multi objective optimization tool. Positive barrier by recharging the water into aquifer using subsurface pond, negative barrier by abstraction of saline water and combination of these two are the three scenarios that are optimally assessed in this study. In the descriptive case study considered, the results indicate that application of treated waste water (TWW) as source of recharge increases the efficiency and the practical value of combined management scenario to control SWI.

INTRODUCTION

The SWI is one of the most challenging environmental problems which threat the quality and availability of freshwater in coastal aquifer, especially, in arid and semi-arid zones of the world. The anthropogenic factors of the modern world such as unplanned exploitation of groundwater intensify the negative impacts of SWI. As a result, groundwater resources should be protected from saltwater intrusion using appropriate measures. Bruington (1972) and Todd (1974) list different methodologies that attempt to control SWI in aquifers. These include reduction of pumping rates, relocation of pumping wells, installations of subsurface barriers, deep recharge using a line of injection wells along the coast, pumping of saline water along the seacoast and combination techniques. The efficiencies of some of these control methods have been investigated by integrating the simulation models with optimization tools to address long-term planning of groundwater management problems. Ataie-Ashtiani and Ketabchi (2011) present a review of the previous research works carried out on the simulation-optimization (S/O) modelling for control of SWI.

The present study investigates the efficiencies of different management methods to control SWI in unconfined aquifers using S/O technique. In addition, by utilizing the unsaturated flow in vadose zone and by focusing on the use of TWW as a more economic source of water for recharging the aquifer, a new combined methodology is introduced for SWI that includes Abstraction, Desalination and Recharge by TWW (ADRTWW)). In the S/O process, Non-dominated sorting genetic algorithm (NSGA-II) is integrated with SUTRA (Voss and Provost, 2010) to assess three different management scenarios of SWI control: (i) Recharge only, (ii) abstraction only and (iii) combined abstraction and recharge. The S/O process is aimed to find the optimal solutions for these three approaches in an hypothetical case study in vertical section. The objectives of the optimization process include minimizing the total construction and operation cost of management scenarios, minimizing the total mass of salt in the aquifer.

MODEL DESCRIPTION

The descriptive model of unconfined aquifer considers a 2D domain with dimensions 200*100 m. As future plan the system will require one production well to pump fresh water with constant rate of 26 m^3/day at location of 40m from inland boundary and at depth 30 m below ground surface. Figure 1, shows the location of this production well and the resulted salinity in the aquifer under steady state condition before and after pumping. The total calculated mass of solute in the aquifer would be raised from 27 tons prior the pumping to 98 tons after pumping. Accordingly, and as it illustrated from Figure 1 the system and a designed production well are threaten by SWI. In order to alleviate this problem the management action required to be taken to comply with the planned demands of water while protecting the system against SWI.

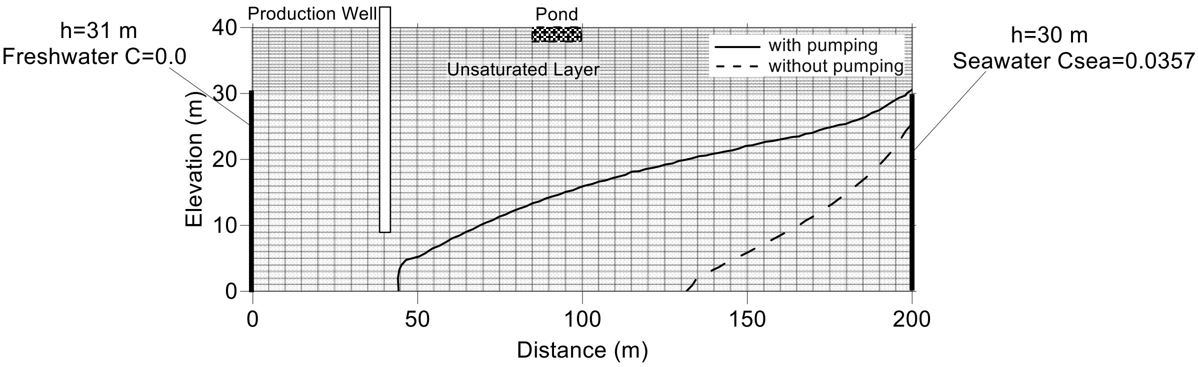

Figure 1. Pre and post-pumping distribution of salinity (0.5 isochlors).

FORMULATION OF OPTIMIZATION MODELS

Three management models (recharge only, abstraction only and combination of abstraction and recharge) are proposed as hydraulic barriers to restrict the negative aspects of the intruded saline wedge during the pumping of freshwater from production well. The S/O model is developed by direct linking of the numerical model with the NSGA-II. The S/O process aims to minimize the total mass of salt (f_1) in the aquifer as well as minimizing the costs (f_2) of construction and operation of the management process. Based on available parameters in each scenario, the objective functions and the set of used constraints are expressed mathematically as follows:

$$\min f_1 = \sum_{i=1}^{N} C_i v_i \tag{1}$$

Management Model 1: Recharge by TWW (Recharge only Scenario)

$$\min f_2 = QR*(CR + MPTW)*\Delta t + CP + CPM \tag{2}$$

Management Model 2: Abstraction followed by desalination (Abstraction only Scenario)

$$\min f_2 = DA*CD + QA*(CA + CT)*\Delta t - r*QA*MPT*\Delta t \tag{3}$$

Management Model 3a: ADR (Combined Scenario)

$$\min f_2 = QR*CR*\Delta t + DA*CD + QA*(CA + CT)*\Delta t - (r*QA - QR)*MPT*\Delta t + CP + CPM \tag{4}$$

Management Model 3b: ADR TWW (Combined Scenario)

$$\min f_2 = QR*(CR + MPTW)*\Delta t + DA*CD + QA*(CA + CT)*\Delta t - r*QA*MPT*\Delta t + CP + CPM \tag{5}$$

Subject to: 0.0<QA(m^3/day) < 52.0 ;0.0 <LA(m) < 200.0;10.0 <DA(m) < 40.0,0.0 <LR(m) < 200.0;Concentration at abstraction location > 0.5 C_{sea}; and total mass of salt *(f_1 or Total C)* < 27.0 tons (total *C* for no management condition before designing the production well). Where:

$f_{1,2}$	:management objective functions	CR	:cost of artificial recharge ($0.12/m^3)
N	:total number of nodes in the domain	CA	:cost of abstraction ($0.42/m^3)
C_i	solute concentration at node i	CT	:cost of desalination ($0.6/m^3)
v_i	:cell volume at node i	CD	:cost of installation/drilling of well ($200 /m)
QA	: abstraction rate (m^3/sec)	CP	: cost of pond construction ($350)
QR	: recharge rate (m^3/sec)	MPT	: market prices of desalinated water ($1.5/m^3)
LR	: horizontal distances of the recharge pond from the left boundary	MPTW:	market prices of TWW ($0.25/m^3)
LA	: horizontal distances of the abstraction well from the left boundary	CPM	: annual cost of maintenance and cleaning of pond (assumed to be 10% of CP)
Δt	: duration of management process (10 years)	r	: recovery ratio of desalination plant (60%)

Appropriate cost values are taken from literature (Javadi et al, 2012). In the management model 1 the TWW with total dissolved solids (TDS) of 1300 mg/l (0.0013 kg_s/kg_f) is artificially recharged by defining a subsurface pond with 15.0 m long and 2.0 m deep to replenish 2.0 m constant head of water in aquifer (Figure 1). The average rate of recharge which is calculated by SUTRA directly under pond is 0.35 m/day. As illustrated in Equation 2, this model has a fixed cost function (f_2) corresponding to this constant rate of recharge. This results in reducing the number of objective functions of the management model 1 to one (only f_1). Also, the location of pond (LR) is the only decision variable in recharge scenario; therefore the optimal value of $f1$ can be readily obtained through parametric study instead of optimization. In this case trade-off of pond location against total solute mass in system (f_1) is found by changing the pond locations along the length of the domain (Figure 2). The location of pond at (110.0-140.0) m from the landside is recommended as the environmentally friendly outcomes of the recharge scenario.

In the abstraction only scenario (Model 2) the brackish water is continuously abstracted from the saline zone followed by the desalinization process to serve the human and irrigation demands. Therefore, the benefit earned from selling of this desalinated water is included with negative sign in its cost function. And finally in the third scenario the efficiency of the management models 1 and 2 in controlling of the SWI are combined. The two different schemes are considered and assessed in combined scenario: i) Abstraction of saline water followed by desalination and recharging the aquifer with the same desalinated water (ADR), and ii) Abstraction of saline water followed by desalination and recharging the aquifer with external and cheap source of water such as treated waste water (ADRTWW). Based on optimal results for location of pond (110.0 m to 140.0 m) obtained in management models 1, the location of recharge basin (LR) in combined scenarios are considered fixed at distance 120m from left boundary in order to guarantee the maximum efficiency from the pond. The first scheme (ADR) is proposed by Javadi et al (2012) as effective and economic method for controlling SWI.

RESULTS

The results of the recharge scenario show that the associated cost of artificial recharge by TWW is 7386 $ for the considered period of time (Δt=10 years). The recharge basin is failed to satisfy the efficiency requirements of the management process or to control salinity levels under 27 tons which is obtained from pre-pumping condition. However, it maintains the total mass of solute in the system lower than the level resulted by steady state condition of post-pumping. The later positive aspect of recharge scenario simultaneously with conclusive outcome of abstraction scenario would enhance the efficiency of the management process in combined scenario. The Pareto fronts (the optimal solutions) obtained from S/O process in the management models 2 and 3 are illustrated in Figure 3. The both scenarios successfully prevent the intrusion of salt water. The second scheme of the combined scenarios (ADRTWW) shows a significantly greater efficiency in terms of minimizing the total cost and concentration than all other strategies. Application of the all produced water from desalination plant directly to meet the consumption needs; and also the relatively low cost of the TWW itself are the responsible factors for the positive progression of the ADRTWW scheme than other scenarios. Consequently, the ADRTWW management methodology is recommended to control the SWI trend in unconfined aquifer systems with small thickness.

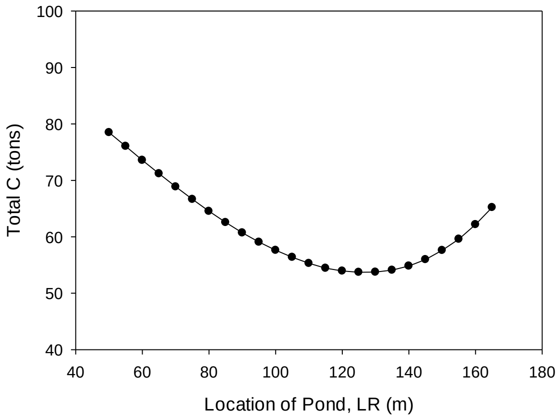

Figure 2. Total concentration vs. the pond locations in recharge scenario.

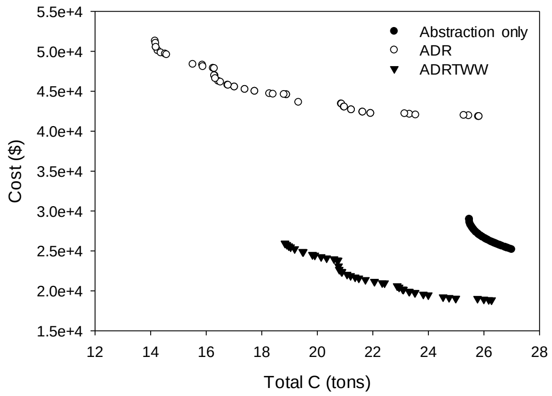

Figure 3. Pareto fronts of Abstraction and combined scenarios.

DISCUSSION AND CONCLUSIONS

The response of an unconfined aquifer to different management scenarios of controlling SWI was investigated using S/O process. A new integrated methodology ADRTWW was proposed to control SWI in unconfined aquifers. The main distinguishing feature of ADRTWW is to collect TWW in percolation ponds and use it as the source of recharge instead of deep injection. The results show that for the case study considered, the proposed methodology controls SWI with the least cost and least salt concentration.

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