Multi-Objective Optimization of Different Management Scenarios to Control Seawater Intrusion in Coastal Aquifers

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Abstract

Seawater intrusion (SWI) is a widespread environmental problem, particularly in arid and semi-arid coastal areas. Therefore, appropriate management strategies should be implemented in coastal aquifers to control SWI with acceptable limits of economic and environmental costs. This paper presents the results of an investigation on the efficiencies of different management scenarios for controlling saltwater intrusion using a simulation-optimization approach. A new methodology is proposed to control SWI in coastal aquifers. The proposed method is based on a combination of abstraction of saline water near shoreline, desalination of the abstracted water for domestic consumption and recharge of the aquifer by deep injection of the treated wastewater to ensure the sustainability of the aquifer. The efficiency of the proposed method is investigated in terms of water quality and capital and maintenance costs in comparison with other scenarios of groundwater management. A multi-objective genetic algorithm based evolutionary optimization model is integrated with the numerical simulation model to search for optimal solution of each scenario of SWI control. The main objective is to minimize both the total cost of management process and the total salinity in aquifer. The results indicate that the proposed method is efficient in controlling SWI as it offers the least cost and least salinity in the aquifer.

Keywords: seawater intrusion, simulation-optimization, multi-objective genetic algorithm, treated wastewater, management scenarios

1. Introduction

Saltwater intrusion is a major problem threatening groundwater resources in coastal areas throughout the world. It is defined as the encroachment of saline water into fresh groundwater domain in coastal aquifer systems. The problem is exacerbated by over-abstraction which eventually can lead to other problems such as decrease of fresh water availability, human health and ecosystem damage (Patel and Shah 2008). Under natural conditions, flux of salt is controlled by the density gradient between the fresh and saline water bodies. The seawater with higher density displaces the deep freshwater and moves along the floor of the bed. The displaced freshwater with lower density moves to upper regions and in order to maintain the dynamic equilibrium of the system it leaves the aquifer as submarine groundwater discharge. Therefore the general pattern of flow in the system near the coast is cyclic where some of saline water is entrained within the overlying freshwater and returned to the sea, causing further intrusion of seawater (Bobba 1993; Sherif et al. 1990a).

Sherif et al. (1990b) and Bear and Zhou (2007) explained that as a result of mechanical dispersion, the contact zone between the two fluids takes the form of a transition zone, the thickness of which depends upon the hydrodynamics of the aquifer. The mixing zone is controlled by transport process components including, among others, density gradients, diffusion, dispersion, and kinetic mass transfer. However, under certain circumstances, where the width of mixing zone is relatively smaller than the aquifer thickness, the boundary can be considered as a sharp interface (where the two liquids may be considered as two immiscible fluids) with a slope which analytically can describe the shape of saline wedge (Das and Datta 1999; Kacimov and Sherif 2006).

Based on these two forms of saline/freshwater interface, in last decades, several methods have been proposed to simulate the SWI process using different analytical, numerical and physical approaches. The Ghyben–Herzberg theory is the first analytical formulation of SWI that allows a quick estimation of the equilibrium location of freshwater/seawater interface, based on sharp interface assumption and under hydrostatic pressure distribution (Bear et al. 1999). Van Dam (1983) proposed sets of analytical formulae for prediction of the fresh-saline interface in unconfined, confined and semi-confined aquifers, where a combination of Darcy's law, continuity and Ghyben–Herzberg equations was used in the derivation of the governing equations (Oude Essink 2001).

The Ghyben–Herzberg assumptions were used in the majority of analytical solutions. However, saltwater intrusion is a highly nonlinear process. Therefore, in recent years, several numerical codes and software were developed successfully to solve the nonlinear flow and solute transport equations under steady state and transient conditions and in both 2D and 3D. SUTRA (Voss 1984), MODFLOW (McDonald and Harbaugh 1988), FEMWATER (Lin et al. 1997), SEAWAT (Guo and Langevin 2002) are among the most widely used models.

Finding a suitable method for controlling the dynamic imbalance between freshwater and saline water has become a priority for many professionals in the field. To control saltwater intrusion, a seaward hydraulic gradient should be maintained and a proportion of the fresh water should be allowed to flow into the sea. The management of a coastal aquifer is the identification of an acceptable ultimate landward extent of the saline water and the estimation of the appropriate discharge of freshwater required to maintain the saltwater/freshwater interface in seacoast position. Todd (1974) and Sherif and Hamza (2001) listed different methodologies that attempt to control SWI in confined aquifers. These include reduction of pumping rates, relocation of pumping wells, use of subsurface barriers, natural and artificial recharge, pumping of intruded saline water and combination techniques. Some of these methods with high rates of saline water pumping, require the disposal of the abstracted salts to reduce environmental problems (Bruington 1972).

Different simulation models (or meta models) have been combined with evolutionary algorithms such as genetic algorithm (GA) to optimize different management schemes to limit SWI. The genetic algorithm has the capability to deal with a wide range of optimization problems. Ataie-Ashtiani and Ketabchi (2011) summarized the research efforts related to simulation-optimization modelling for control of saltwater intrusion. Some works are based on sharp interface theory through analytical and FE methods (e.g., Cheng et al. (2000); Benhachmi et al. (2003); Park and Aral (2004) and Ferreira da Silva and Haie (2007)). Others used 2D or 3D variable density models (e.g. Das and Datta (1999); Lin et al. (2009); Kourakos and Mantoglou (2009; Kourakos and Mantoglou 2011); Qahman et al. (2009); Sreekanth and Datta (2010) and Javadi et al. (2012)). A number of researchers also used artificial neural networks (e.g. Rao et al. (2004); Bhattacharjya et al. (2007); Bhattacharjya and Datta (2005; 2009); Dhar and Datta (2009); Sreekanth and Datta (2010) and Banerjee et al. (2011)) with genetic algorithm.

Although most management problems are multi-objective, the objective functions are usually aggregated into one (Abd-Elhamid and Javadi 2011; Park and Aral 2004; Qahman et al. 2009), to use simple genetic algorithm. In this algorithm different individual solutions can be considered as optimal by changing penalty factors (weights). Therefore, selection of the most appropriate weights requires further repetitive trails. Also, simulation-optimization with simple genetic algorithm is computationally time demanding. Therefore the use of multi-objective optimization would be preferable. In a multi-objective optimisation Pareto-optimal solutions trade different objectives against each other and no improvement in any objective function is possible without sacrificing the other objective functions (Gen and Cheng 1996). Non-dominated sorting genetic algorithm (NSGA-II) developed by Deb et al. (2002) is one of the most widely used multi-objective evolutionary algorithms.

Dhar and Datta (2009) and Sreekanth and Datta (2010) used NSGA-II to minimize the rate of flow of barrier wells located near to coast and to maximize the total abstraction rates in production wells located inland. In order to ensure uniform sampling of the bound space, the NSGA-II algorithm was modified by Dhar and Datta (2009) to generate initial population for pumping rates using the Latin hypercube sampling (LHS) strategy. They linked this modified optimization tool to simulation models in three different schemes. In first scheme they linked it with the FEMWATER numerical model and in others with a fully and partially trained artificial neural network. Sreekanth and Datta (2010) used genetic programming and modular neural network as meta model to work with NSGA-II using the same management scenario.

2. Objective of the Study

This paper focuses on development and application of a simulation–optimization technique to assess the efficiencies of different management methods to control SWI. The treated wastewater (TW) is used for aquifer recharge (injection) as an economic water sources for adjusting the hydraulic heads and preventing the seawater from advancing further inland. A new integrated methodology, composing of Abstraction, Desalination and Recharge by TW (ADR-TW) is proposed to control the SWI in coastal aquifers. The proposed methodology consists of three steps; abstraction of brackish water from the saline zone, desalination of the abstracted brackish water to meet the projected water demand, and artificial recharge of the TW into the aquifer. This methodology is an extension of the method proposed by Abd-

Elhamid and Javadi (2011), known as ADR in which they used desalinated water as a source of water for recharge. In addition, a multi-objective optimization is used and a set of different management scenarios are considered and compared in the present study.

The efficiency of the proposed methodology (ADR-TW) is investigated and compared with ADR and other management scenarios through simulation-optimization. For this purposes, the NSGA-II is linked with the SUTRA model to examine three different management scenarios of SWI control: pumping (of brackish or intruded saline water) only, recharge only and combined abstraction and recharge with different schemes. The objectives of the developed simulation-optimization model include minimizing the total economic cost of management scenarios and minimizing total amount of salinity in the aquifer besides determining the optimal depths, locations and abstraction/recharge rates in each scenario.

3. Simulation-optimization methodology

In the present work the simulation model (SUTRA) was integrated with NSGA-II to identify the optimal arrangements for the proposed seawater control method. The general forms of fluid flow and solute transport governing equations of simulation model that developed by Voss and Provost (2010) are presented in the appendix. In the proposed simulation-optimization process, the NSGA-II repeatedly calls numerical model to compute state variables in response to each set of randomly generated design variables. After computing the objective function and evaluating its fitness, the values of decision variables are updated using the main evolutionary processes (selection, crossover and mutation) of genetic algorithm and thus the best solutions from mating pool of parent and offspring populations are selected. NSGA-II organizes the members of the population into nondominated fronts after each generation, based on the conflicting objectives of optimization. The new values of decision variables are then returned to simulation model and the process is repeated until it satisfies optimal criteria or it reaches the maximum generation and finally it captures the Pareto of optimal solutions for the problem (Deb et al. 2002).

4. Application

The developed evolutionary simulation-optimization framework is applied to one of the most widely used benchmark problems of saltwater intrusion (Henry's problem). This case study, involves SWI 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 boundaries of aquifer (Voss and Provost 2010). The idealized aquifer for the Henry’s problem is shown in Figure 1. A summary of the parameters is presented in Table 1 according to Hughes and Sanford (2004). The domain, 200 m in length and 100 m in height, was discretized using 1250 elements (each of size 4m×4m) and 1326 nodes. Freshwater concentration (C_o=0) and natural steady-state pressures were initially set everywhere in the aquifer. The system essentially reached a steady state after 400 time steps, with a time step of 100 minutes. Figures 2a and b illustrate the steady state variations of concentration and hydraulic head throughout the system, respectively. The total calculated mass of solute in the aquifer is 106 tons.

5. Formulation of management models

The aquifer is subjected to three different management scenarios: recharge only, abstraction only and combination of abstraction and recharge. The efficiency of each scenario in term of controlling saline water encroachment is investigated and compared. Different schemes are considered for each scenario as follows:

i. Recharge only:
  a) Recharge by desalinated water

   b) Recharge by treated wastewater (TW)

ii. Abstraction only: Abstraction of brackish water and its disposal to sea.

iii. Abstraction + Recharge :

   a) Desalination of abstracted water + recharge by excess of desalinated water (ADR)
   b) Desalination of abstracted water + recharge by TW (ADR-TW)
   c) Abstraction of brackish water and its disposal to sea + recharge by TW

In the third scenario, the ADR is based on continuous abstraction of intruded salt water, desalination of the abstracted water and use for recharge. The small part of this desalinated water is intended for recharge and the rest of the water is used for general human consumption (Abd-Elhamid and Javadi 2011). In the second scheme, all of the abstracted brackish water is treated and used, and the recharge is implemented using TW. Finally in the third case the abstracted water is disposed to sea directly without any treatment and an external TW is used as the source of artificial recharge.

The simulation-optimization 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 abstraction and recharge wells. The optimization process in each scenario is subject to different constraints on the decision variables. The objective functions for each scenario are represented mathematically by the following equations:

$$\min f_1 = \sum_{i=1}^{N} C_i * v_i \qquad (1)$$

Recharge scenarios:

$$\min f_2 = DR * \beta_d + QR * (\beta_r + \alpha_1) \qquad (2a)$$

$$\min f_2 = DR * \beta_d + QR * (\beta_r + \alpha_2) \qquad (2b)$$

Abstraction scenario:

$$\min f_2 = DA*\beta_d + QA*\beta_a \tag{3}$$

Abstraction + Recharge scenarios:

$$\min f_2 = DR*\beta_d + QR*\beta_r + DA*\beta_d + QA*(\beta_a + \beta_t) - (QA - QR)*\alpha_1 \tag{4a}$$

$$\min f_2 = DR*\beta_d + QR*(\beta_r + \alpha_2) + DA*\beta_d + QA*(\beta_a + \beta_t) - QA*\alpha_1 \tag{4b}$$

$$\min f_2 = DR*\beta_d + QR*(\beta_r + \alpha_2) + DA*\beta_d + QA*\beta_a \tag{4c}$$

where: f is management objective function, N is total number of nodes in the domain, C_i is the solute concentration at node i ,v_i is volume of FE cell at node i, QA and QR are rates (m^3/sec) of abstraction and recharge respectively. DR and DA are depths (m) of recharge and abstraction wells respectively. α_1 and α_2 are market prices (\$/m^3) of desalinated water and TW respectively. β_a, β_r and β_t are costs (\$/m^3) of abstraction, recharge and treatment respectively. β_d is cost (\$/m) of installation/drilling of well.

The total cost is calculated based on the unit cost of installation/drilling of well (\$100 per unit depth), cost of abstraction (\$0.42 per cubic meter), cost of recharge (\$0.48 per cubic meter), cost of desalination (treatment) (\$0.6 per cubic meter), market price of desalinated water (\$1.5 per cubic meter) and market price of TW (\$ 0.25 per cubic meter) (Asano and Bahri 2010; Chen et al. 2003; Javadi et al. 2012).

The first and second scenarios have mainly three decision variables: location, depth and rate of flow in recharge and abstraction wells and the state variables are fluid pressure and solute concentration that are calculated by numerical model at every node in the domain. The third scenario has six parameters as combination of all abstraction and recharge parameters, as illustrated in Figure 3. Based on available parameters in each scenario the following side constraints were considered for the model:

$$0 < QA, QR\,(m^3/\sec) < 0.005 \tag{5}$$

$$0 < LA, LR\,(m) < 200 \tag{6}$$

$$0 < DA, DR\ (m) < 100 \tag{7}$$

$$total\ C < 106\ tons\ (total\ C\ for\ no-management\ case) \tag{8}$$

$$LA > LR \tag{9}$$

$$C\ at\ abstraction\ location > 0.5\ C_{sea} \tag{10}$$

The simulation-optimization tool deals with constraints 9 and 10 in the combined management scenario to restrict the abstraction from specific zone of intrusion wedge which has salinity more than 50% of that of seawater. It is predicated that continuous abstraction of brackish water, with high levels of solute concentration, from this zone of the intrusion wedge will be useful for the future sustainability of the system. In NSGA-II equations 8-10 are defined as constraint equations while the other constraints can be easily delineated by bounding the population space of the design variables to be within the given limits. Desalinated water with total dissolved solids (TDS) of 250 mg/l and TW with 1300 mg/l are used for recharge.

6. Results and discussions

In the developed evolutionary simulation-optimization approach, the optimal solutions are addressed by genetic algorithm using 100 generations and population sizes of 100. Also, the probabilities of 0.9 and 0.0025 are used for crossover and mutation respectively to generate the bounded decision variables. The computational time of the analysis was about 3 hours on an Intel(R) Core(TM) i7-2600 CPU @ 3.40GHz (8 CPUs) with 16 GB RAM.

6.1 Recharge scenario: The results for the recharge scenario show that recharge by TW with 1300 mg/l solute concentration has better efficiency than recharge by desalinated water with lower TDS. This is due to the lower market value of TW as compared with desalinated water (Figure 4). In both schemes of this scenario, the seaward location of recharge well is recommended (by the framework) as the most environmentally friendly and economical policy. In terms of optimal rate of recharge, both schemes follow the same trend. Generally, the system incorporating TW recharge requires more quantity of water than the other system involving recharge of desalinated water to control the total mass of solute at the same level. This is attributed to lower levels of concentration in desalinated water as compared to TW.

6.2 Abstraction scenario: The abstraction of saline water and its disposal to sea, controls SWI with lower costs than the recharge scenarios (Figure 5). However, in abstraction scenario there is no significant reduction in the total mass of concentration in the aquifer compared with recharges' scenarios. The optimal location and depth of pumping well are 176-180 m and 96 m, respectively along the line of best solutions. Furthermore, the optimal rates of pumping along this trade off shows a gradual increasing as total mass of solute is reduced.

6.3 Abstraction and recharge scenario: The evidence from this scenario, as shown in Figure 6, indicates that although the ADR could be effective in controlling SWI, it is outperformed by other approaches such as recharge by TW and ADR-TW as shown in Figures 4 and 6, respectively. Conversely, the second method of this combined scenario which involves continuous pumping of saline water, desalination of the abstracted water for domestic and irrigation purposes and recharge of the aquifer with TW within the framework of ADR-TW system offers significantly higher efficiency in terms of minimizing total cost and salt concentration than other combination strategies. Accordingly, and based on optimal location and rates of source/sink obtained from ADR-TW methodology and in order to define the capability of this scenario, the changes in heads and concentrations of this scheme are presented and selected based on engineering judgment in terms of objective functions. The results obtained for both management scenarios in terms of the optimal flow rate, depth and location of the abstraction/recharge wells with the corresponding total costs are summarized in Table 2.

The main aspect of efficiency of this model is about minimization of total concentration of solute in the aquifer as it reduced the total mass of solute in the selected solution by more than 35%. This optimal arrangement justifies all the cost spent on the system by saving more than 20000 $/year from selling the desalinated water. In addition, ADR-TW uses all the abstracted brackish water after its desalination to meet the water demands in the various sectors. The final concentration and head distributions for this model are shown in Figures 7a and 7b, respectively. The results show the seaward advancement of hydraulic head and the retardation of the saline wedge in the aquifer as compared with the no management scenario. Figure 8 compares the performance of this solution in controlling of SWI with no management scenario in the form of 50% isochlor lines.

7. Summary and conclusion

This paper presents the development and application of a simulation-optimization model to assess different management methods of controlling saltwater intrusion. The simulation model was linked with a multi-objective genetic algorithm to optimize control arrangements for a benchmark aquifer (Henry’s Problem). Three different management scenarios were considered to control the SWI. These scenarios involved (i) use of recharge well; (ii) use of abstraction well and (iii) combination of abstraction and deep recharge. The efficiencies of these scenarios were investigated through different schemes. A modified version of ADR management scenario was proposed involving abstraction of saline water near the seacoast together with inland injection of TW to recharge the aquifer.

The objective functions of optimization were to minimize both the total cost of management processes and the total amount of salinity in the aquifer by identifying the optimal locations and depths of abstraction and recharge wells and optimal rates of abstraction and recharge. The results confirm that the proposed method, ADR-TW, provides the least cost and least salt concentration in the aquifer and, in the meantime, maximizes the retardation of freshwater/saline water interface. The movement of seawater body is reversed back to the seaside. In addition, this method requires less volumes of recharge water for optimal control of SWI. Considering the cost of desalination, it would be preferable (more cost-effective) to recharge the aquifer using the TW in real case studies and to use the desalinated water to meet the domestic demands. However, further attention is required on the quality of this reclaimed source of water to reduce the associated health, environmental and economical risks.

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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 (Voss and Provost 2010).The general forms of these equations summarized below:

Fluid mass balance equation:

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

Solute mass balance equation:

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

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]
C_s : specific concentration of adsorbate on solid grains [M_s/M_G]
$\underline{\nabla}$: 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]
$\underline{v}$: 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 [$M/(L.T^2)]^{-1}$

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Table 1: The parameters used in Henry's problem.

D_m	: coefficient of water molecular diffusion [m^2 /s]	18.8571*10^{-4}
Q_{in}	: inland fresh water flux [m^3/s]	6.6*10^{-3}
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
C_{sea}	: solute mass fraction of seawater [kg(dissolved solids)/kg(seawater)]	0.0357
ρ_{sea}	: density of sea water [kg/m^3]	1024.99
ρ_o	: density of fresh water [kg/m^3]	1000
μ	: fluid viscosity [kg/(m.s)]	0.001
α_T, α_L	: transverse and longitudinal dispersivity [m]	0.0

Table 2: Summary of the results obtained from the simulation-optimization models for one solution of proposed ADR-TW model.

Model	**L (m)**	**D (m)**	**Q (m^3/day)**	**Total C (tons)**	**Cost ($/year)***
No Management	-			106	-
Abstraction and Recharge by TW	192 168	92 92	431 135	68	-21130

*-ve value represents the benefit

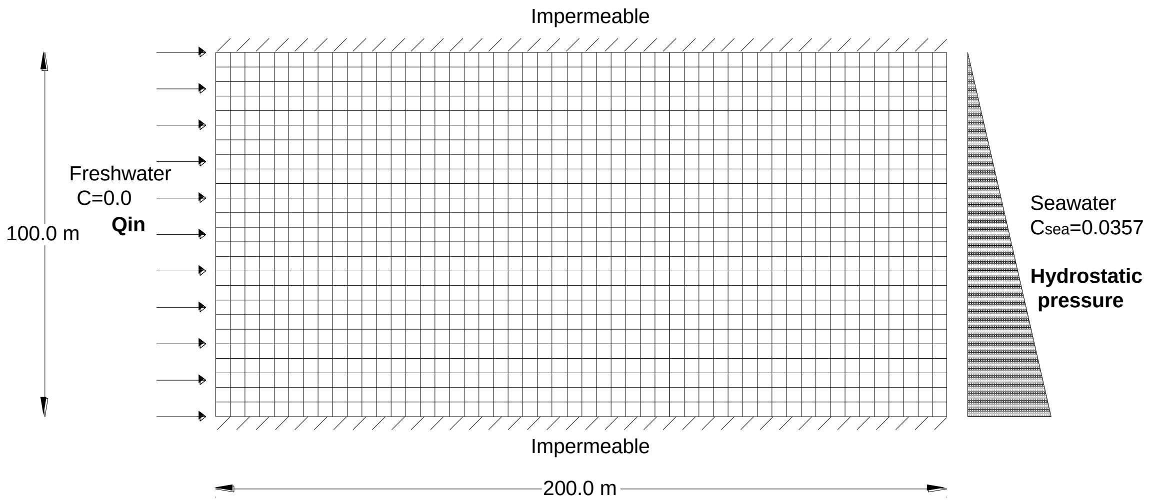
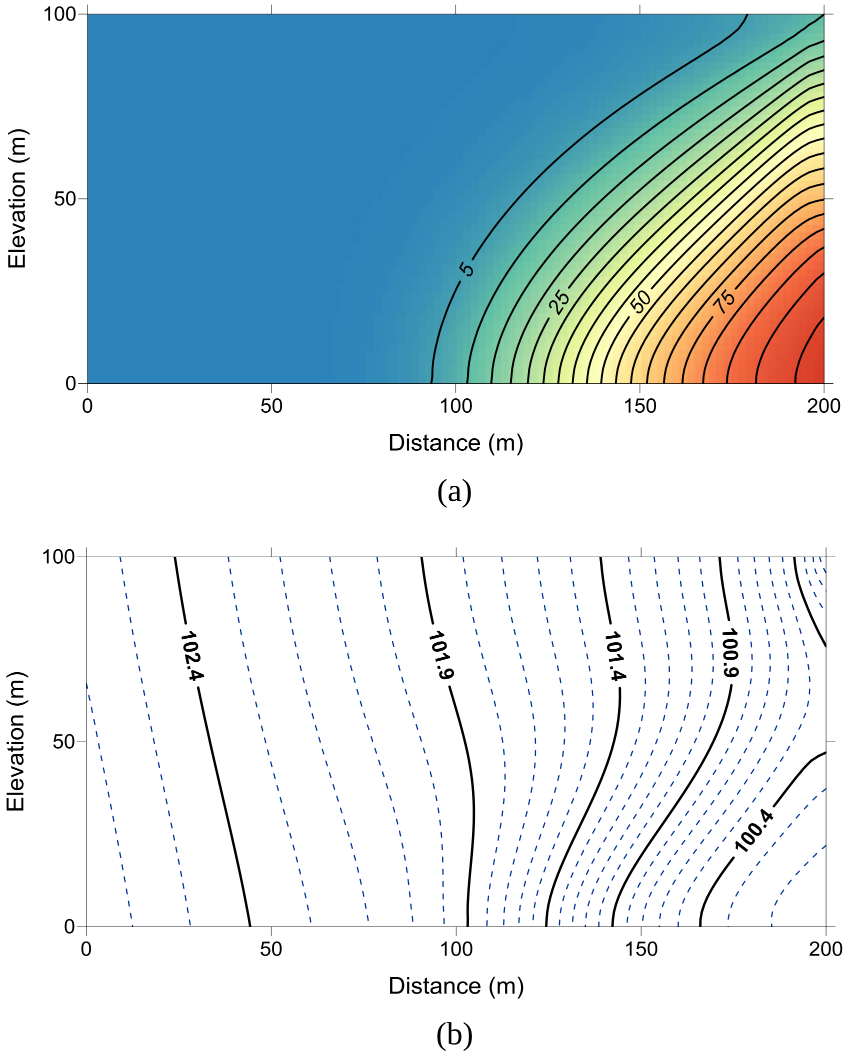


Figure 1: Boundary conditions of the case study (2D).



(a)

(b)

Figure 2: Variation of a) salinity (%) and b) hydraulic head (m) throughout the system in steady state condition.

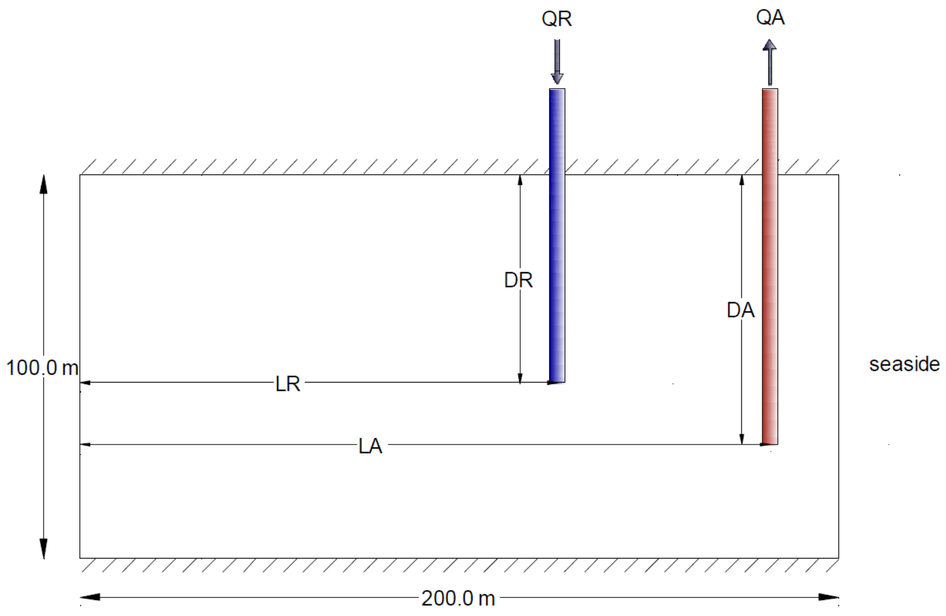


Figure 3: Schematic sketch for available decision variables.

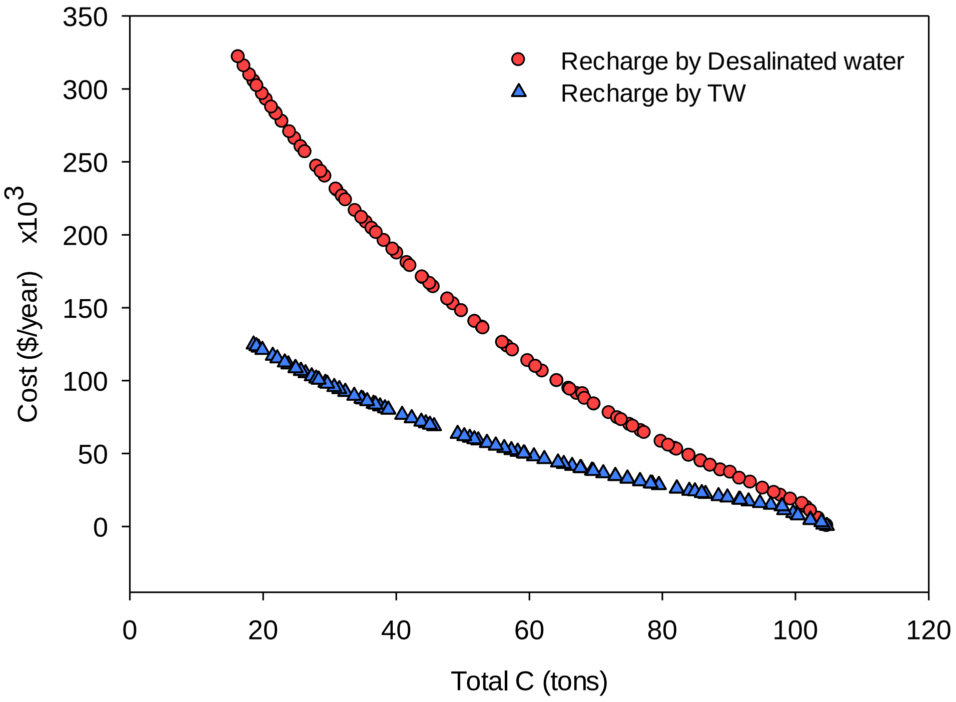


Figure 4: Optimal trade off of recharge scenarios.

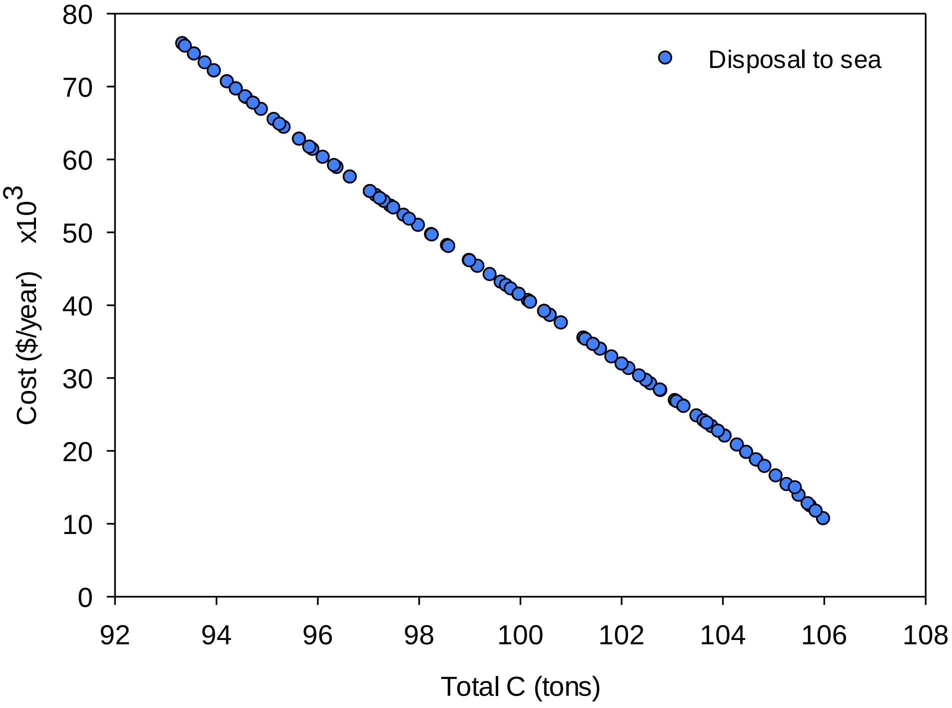


Figure 5: Optimal trade off of abstraction scenarios.

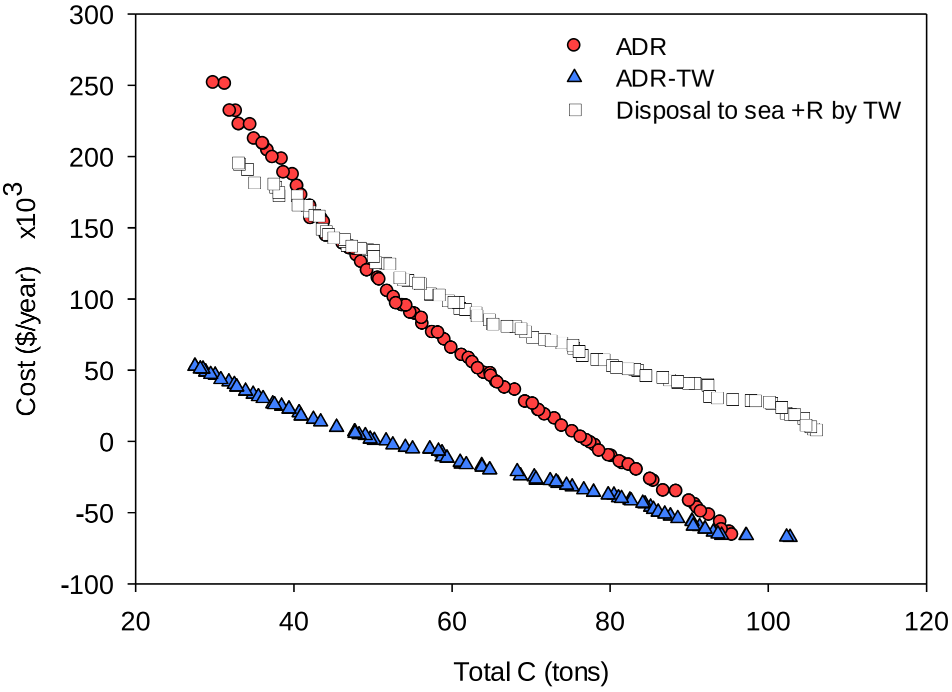
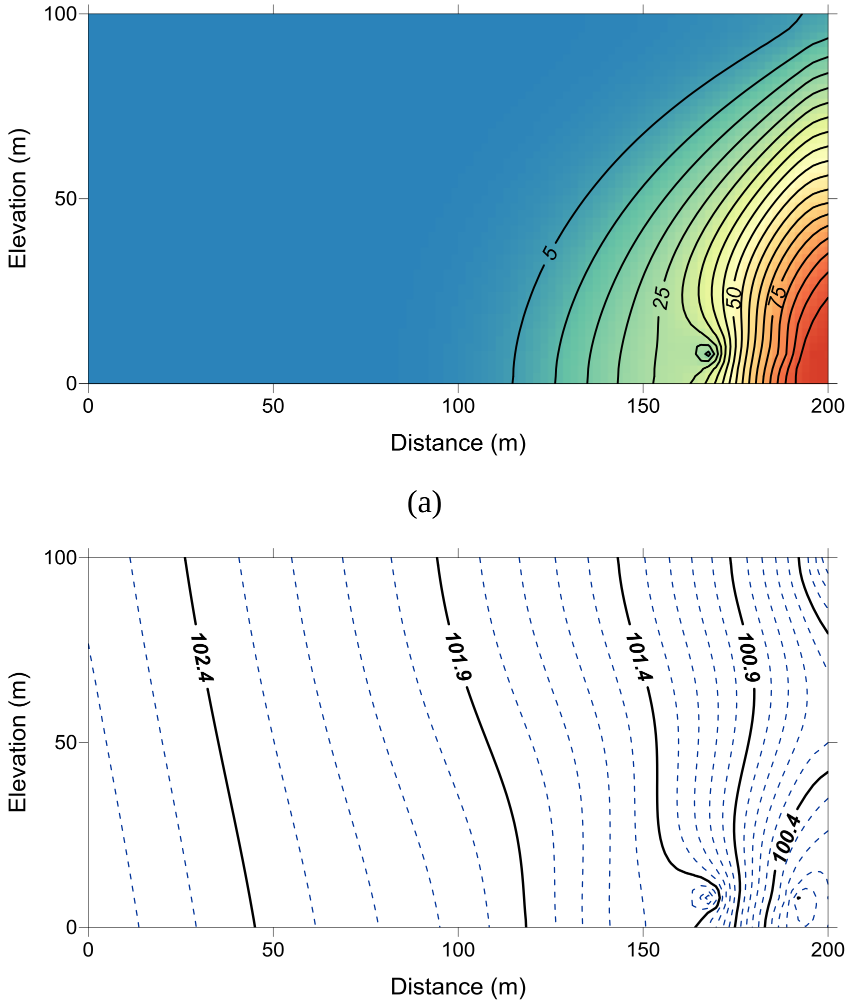


Figure 6: Optimal trade off of abstraction+ recharge scenarios.



(a)

(b)

Figure 7: Steady state variation of a) solute concentration (%) and b) hydraulic head (m) in the system for selected solution of ADR-TW.

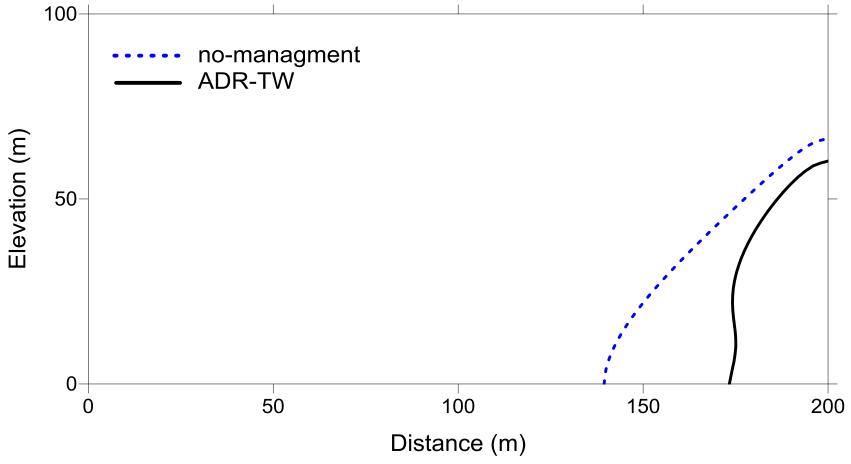


Figure 8: The 50% isochlors for optimal selected solution of ADR-TW and no management scenarios.