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Abstraction, desalination and recharge method to control seawater intrusion into unconfined coastal aquifers

S. Sadjad Mehdizadeh[1,]*, S. Badaruddin[2], S. Khatibi[3]

[1]Department of Civil Engineering, Central Tehran Branch, Islamic Azad University, P.O. Box 13185-768, Tehran, Iran
[2]Civil Engineering Department, Politeknik Negeri Ujung Pandang, P.O. Box 90245, South Sulawesi, Indonesia
[3]Department of Civil Engineering, Sharif University of Technology, Tehran, Iran

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ABSTRACT

In this study, abstraction, desalination and recharge method and SEAWAT numerical model are used to investigate seawater intrusion repulsion in a hypothetical two-dimensional coastal aquifer to understand the relation of seawater intrusion with abstraction, desalination and recharge parameters (i.e. abstraction/recharge rate, wells distance and depth). Abstraction, desalination and recharge consists of abstraction and desalination of brackish water and recharge of desalinated water. The results of different defined scenarios showed that increase of recharge rate has a significant effect on the seawater intrusion mitigation (e.g. more than 80% variation in saline water volume) while the increase of abstraction rate does not have specific impact on seawater recession (e.g. less than 3% variation in toe position). The method efficiency in reducing seawater intrusion is increased when freshwater is recharged by well at outside of saltwater wedge and close to its toe position. Moreover, it is shown that the abstraction, desalination and recharge performance has slightly improved when the recharge and extraction wells are placed deeper into aquifer and close to aquifer bottom (almost 15% for all characteristics of salt wedge). Ultimately, dilution of saline water with recharged freshwater will widen the mixing zone but as salt wedge recedes toward the sea simultaneously, the mixing zone thickness cannot follow the steady reduction trend.

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INTRODUCTION

More than 70% of world population lives in coastal zones (Bear *et al.,* 1999). These areas are confronting several serious hydrogeological problems such as reduction of freshwater storage, groundwater pollution and seawater intrusion (SWI) (Shi *et al.,* 2011, Werner *et al.,* 2013). The rising demand of water supply due to world population growth and the increase of life standard has led to over-abstraction of natural fresh groundwater that followed by further encroachment of saline water into coastal aquifers. Tides, waves, climate changes and sea level rise are other reasons for the increase of SWI (Moustadraf *et al.,* 2008; Werner *et al.,* 2013, Shi *et al.,* 2018). Some SWI controlling methods

*Corresponding Author:
Email: *Saj.Mehdizadeh@iauctb.ac.ir*
Tel.: +9821 4460 0035
Fax: +9821 4460 0071

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that exist are usually chosen based on the extent of saline intrusion, coastal geology, type of water usage and economical factor. For example, optimization of pumping rates and locations, artificial recharge of freshwater, abstraction of saline water and use of subsurface barriers are commonly applied to protect groundwater resources from contamination of seawater (Todd and Mays 2005). Several researches have been carried out to investigate the above mentioned-methods efficiency (e.g. Cheng *et al.,* 2000; Mantoglou 2003; Mantoglou *et al.,* 2004; Mantoglou and Papantoniou 2008; Park *et al.,* 2009; Luyun *et al.,* 2011; Pool and Carrera 2011; Kaleris and Ziogas 2013 and Lu *et al.,* 2017). Abd-Elhamid and Javadi (2011) presented a cost-effective methodology to control SWI called ADR (Abstraction, Desalination and Recharge) method. The ADR method consists of three steps; abstraction of brackish water from the saline water zone, desalination of the abstracted brackish water using methods such as reverse osmosis and finally recharge of the treated water into aquifer. This technique reduces the volume of saline water in aquifers and consequently increases the fresh groundwater storage. To achieve the above purposes, Abd-Elhamid and Javadi (2011) developed a coupled transient density-dependent finite element model to simulate the groundwater flow and solute transport. The model is also integrated with a simple genetic algorithm optimization to evaluate the efficiency of different scenarios in controlling the SWI problem. Three management scenarios are considered in their study: abstraction of brackish water, recharge of fresh water and combination of abstraction, desalination 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 depths, locations and abstraction/recharge rates. The proposed simulation-optimization model focused on showing the efficiency of ADR in controlling SWI compared to other methods. However, in terms of effectiveness of the method in reducing SWI (e.g. how the injected freshwater dilutes the brackish water), the total required time for ADR method to be efficient and the amount of increased fresh groundwater level and volume over time are not discussed in their study. Following the same approach, Javadi *et al.,* (2015) investigated the efficiency of the new version of ADR method distinguished by application of treated wastewater (TW) instead of desalinated water for recharging purpose. The modified ADR method (ADR-TW) consists of three steps: abstraction of brackish water from saline zone, desalination of abstracted brackish water to meet the projected water demand (e.g. industrial and agricultural) and recharge of TW (i.e. treated waste or contaminated surface water) into the aquifer. The new developed simulation-optimization model applied to Henry’s hypothetical aquifer and the results are compared with ADR methodology proposed firstly by Abd-Elhamid and Javadi (2011). They concluded that the ADR-TW provides the least cost in comparison to ADR method and the most saltwater retardation in the aquifer in comparison to separate recharge or abstraction scenarios. Since modelling conceptualization should be accomplished first to understand the sensitivity of coastal groundwater management (Ketabchi and Ataie-Ashtiani 2015), the current study is attempted to evaluate the efficiency of ADR method (regardless of cost optimization) in combating SWI, in response to variations of involved parameters (i.e. abstraction/recharge rate, wells distance and depth) in a two dimensional hypothetical coastal aquifer. Reduced volume of seawater, toe position and freshwater-seawater mixing zone thickness are measured in this study, in response to changes of the extracting/recharging rates and wells positions. This study has been carried out in Tehran, Iran in 2018.

MATERIALS AND METHODS

Finite difference dispersive SEAWAT model

SEAWAT modelling code is developed by Langevin *et al.,* (2008) for simulating density-dependent flow and solute transport in saturated porous media and it has been used by many researchers in recent years (e.g. Post *et al.,* 2013; Mehdizadeh *et al.,* 2014; Badaruddin *et al.,* 2015, 2017). The flow equation is solved with finite difference MODFLOW model (Harbaugh 2005) and solute transport equation is solved by MT3DMS model (Zheng and Wang 1999). SEAWAT couples the flow and transport equations through fluid density term. It has been validated by Henry, Elder and Hydrocin benchmark problems (Langevin *et al.,* 2008).

Two dimensional Hypothetical regional-scale aquifer

A vertical two dimensional large-scale unconfined aquifer has been simulated to investigate the influence of depths and locations of abstraction/recharge wells and rates of abstraction/recharge used in the ADR method in controlling SWI. The aquifer geometry and physical properties are adopted from a conceptual model that is firstly introduced by Werner and Simmons (2009). The homogeneous aquifer is 1000 m long and sea level is 30 m (measured from the aquifer base: Fig. 1). The 1.0 m width (perpendicular to cross section presented in Fig. 1) is considered to apply recharge from rainfall and well rates (i.e. abstraction and recharge) at cell centre with their units, L/T and L^3/T, respectively. The soil and fluid parameters used in the model are summarized in Table 1.

Time steps for groundwater flow and solute transport equation are 10 and 2 days, respectively. To choose the proper grid size, it is necessary to use acceptable criteria for simulation accuracy and mixing zone thickness precision (Diersch and Kolditz 2002, Goswami and Clement 2007). To achieve the goal, Peclet number (P_e) should be less than 4 (Voss and Souza 1987). Δx=2.0 m and Δz= 0.5 m satisfied the grid size criteria for the current model. The total freshwater inflow is subdivided to 60 cells and applied to 30 m landward boundary as an artificial injection wells. To prevent non-convergence solution in transient simulations, a layer at 2.0 m height is added to the top of aquifer (i.e. base of layer equals to 30.0 m). Specific yield (S_y) applied only to this layer as it contains groundwater surface. Specific storage ($S_s[L^{-1}]$) is assigned to the rest of lower layers cells. Flow and solute equations are explicitly coupled and Courant number is set to 0.75. Steady and transient states are achieved in two stages. The total time for the first stage (i.e. before implementing the ADR) is 200 years. This time should be appropriate and long enough for the system to reach the steady-state condition. Head and concentration distributions at the end of steady state (first stage) are used as the initial conditions in the transient simulation. In the transient modelling (second stage), the ADR scenario is first set and then the model is run under transient condition for 50 years. The injected freshwater is assumed has no salinity with 1000 kg/m^3 of density.

Table 1. The parameters used in the simulation of hypothetical aquifer

Parameters	Values
Freshwater density, ρ_f (kg/m^3)	1000
Seawater density, ρ_s (kg/m^3)	1025
Seawater concentration, C_0 (kg/m^3)	35
Seawater initial head, h_{s0} (m)	30
Longitudinal dispersivity, α_L (m)	1.0
Transverse dispersivity, α_T (m)	0.1
Hydraulic conductivity, K (m/d)	10
Porosity, n (-)	0.35
Freshwater inflow, Q_{in} (m^3/d)	0.12
Anisotropy ratio	1.0
Specific storage, S_s (m^{-1})	0.0008
Specific yield, S_y (-)	0.2
Rainfall recharge, R(m/d)	5×10^{-5}

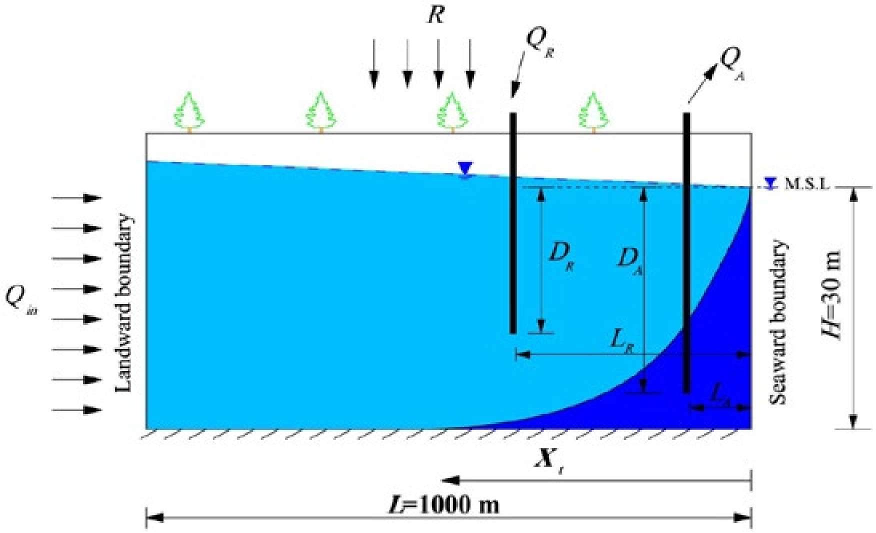

Fig. 1. The geometry and boundary conditions of hypothetical aquifer model

Table 2. Different management scenarios used to evaluate the efficiency of ADR

Scenario	L_A(m)	L_R(m)	Q_A(m^3/d)	Q_R(m^3/d)	D_A(m)	D_R(m)
1	50	670	0.4	0.1	30	30
2	50	670	0.25	0.2	30	30
3	50	670	0.4	0.3	30	30
4	50	670	0.4	0.2	30	30
5	100	670	0.25	0.2	30	30
6	100	870	0.25	0.2	30	30
7	100	400	0.25	0.2	30	30
8	100	200	0.25	0.2	30	30
9	50	670	0.3	0.2	30	30
10	50	670	0.5	0.2	30	30
11	50	400	0.4	0.3	15	30
12	50	200	0.4	0.3	30	15
13	50	200	0.4	0.3	15	15
14	50	400	0.4	0.3	15	15
15	50	400	0.4	0.3	15	5

According to Fig. 1, a sensitivity analysis is performed on six parameters: abstraction rate (Q_A), recharge rate (Q_R), abstraction well distance from shoreline (L_A), recharge well distance from shoreline (L_R), abstraction well depth (D_A) and recharge well depth (D_R) (depths are measured from sea level). Definition of these six parameters is presented in Fig. 1. Fifteen different management scenarios are defined based on number of variables and available positions of wells considering the limitation of aquifer geometry due to amount of intruded seawater (Table 2). The six main parameters are made dimensionless for better comparison according to Table 3.

Table 3. List of dimensionless parameters introduced in ADR method

Dimensionless parameter	Symbol
L_A/L_{aq}	P_{AL}
L_R/L_{aq}	P_{RL}
Q_A/Q_{in}	P_{AQ}
Q_R/Q_{in}	P_{RQ}
D_A/H	P_{AH}
D_R/H	P_{RH}

L_{aq} is aquifer length and H is aquifer height at the vicinity of the shoreline

Three parameters as the ADR efficiency indicators have been measured to compare scenarios output: 1) salt wedge toe position (X_t [L]), which is the intersection position of $0.5C_0$ salinity contour line and aquifer bed (Luyun *et al.,* 2011; Morgan *et al.,* 2013), 2) The amount of saline and brackish water volume that remains in the aquifer (V_s [L^3]), where salinity concentration is greater than $0.05C_0$ and 3) The average mixing zone thickness (W_t [L]). W_t is defined by salinity concentration greater than $0.05C_0$ and less than $0.95C_0$, which can be achieved by dividing the mixing zone area (A_t [L^2]) to the mixing zone length (L_t [L]). The L_t parameter is considered to be the distance of $0.5C_0$ contour line at top and bottom of aquifer. Lu *et al.,* (2013) bounded the A_t by $0.1C_0$ and $0.9C_0$ and Kaleris and Ziogas (2013) used a less than $0.014C_0$ criterion as an index for freshwater definition. In this study, the A_t domain is extended to the zone with salinity greater than $0.05C_0$ and less than $0.95C_0$. X_t and V_s are made dimensionless to simplify the comparison as described by Eqs. 1 and 2.

$$\mathrm{X_r} = \left(\frac{\mathrm{X_{t0}} - \mathrm{X_t}}{\mathrm{X_{t0}}}\right) \times 100 \tag{1}$$

$$V_{rs} = (\frac{V_{s0} - V_s}{V_{s0}}) \times 100 \tag{2}$$

Where, X_{t0} and V_{s0} are respectively the salt wedge toe position and the saline volume extent at the end of steady-state simulation (i.e. before applying ADR).

RESULTS AND DISCUSSIONS

Distance of abstraction and recharge wells from sea

Analyses of different abstraction and recharge wells distance from the sea boundary are presented in Fig. 2. According to Fig. 2 (a) to (c) that show the comparison results of scenario 2 with P_{AL}=0.05 and scenario 5 with P_{AL}=0.1, the larger the distance of abstraction well's position from the coastline, the better ADR efficiency is produced. Although the differences in the results are not significant, especially for early times, but having the abstraction well closer to available X_{to} (i.e. 557 m) may pull the saline water at vicinity of the toe towards the well and causes faster movement of replacing freshwater. More dilution then occurs and seaward saltwater wedge movement is more obvious. Fig. 2(b) shows that pulling the saline water towards the well that is located at the outside of salt wedge causes thicker mixing zone, even though the volume of freshwater is increased continuously due to freshwater-brackish water dilution. In reality, most desalination plants are placed close to the shoreline to directly purify the saline water from sea instead of aquifer. Thus, having the desalination plants placed farther from the shoreline may limit the plants to be working maximally. Considering multi-objective usage of

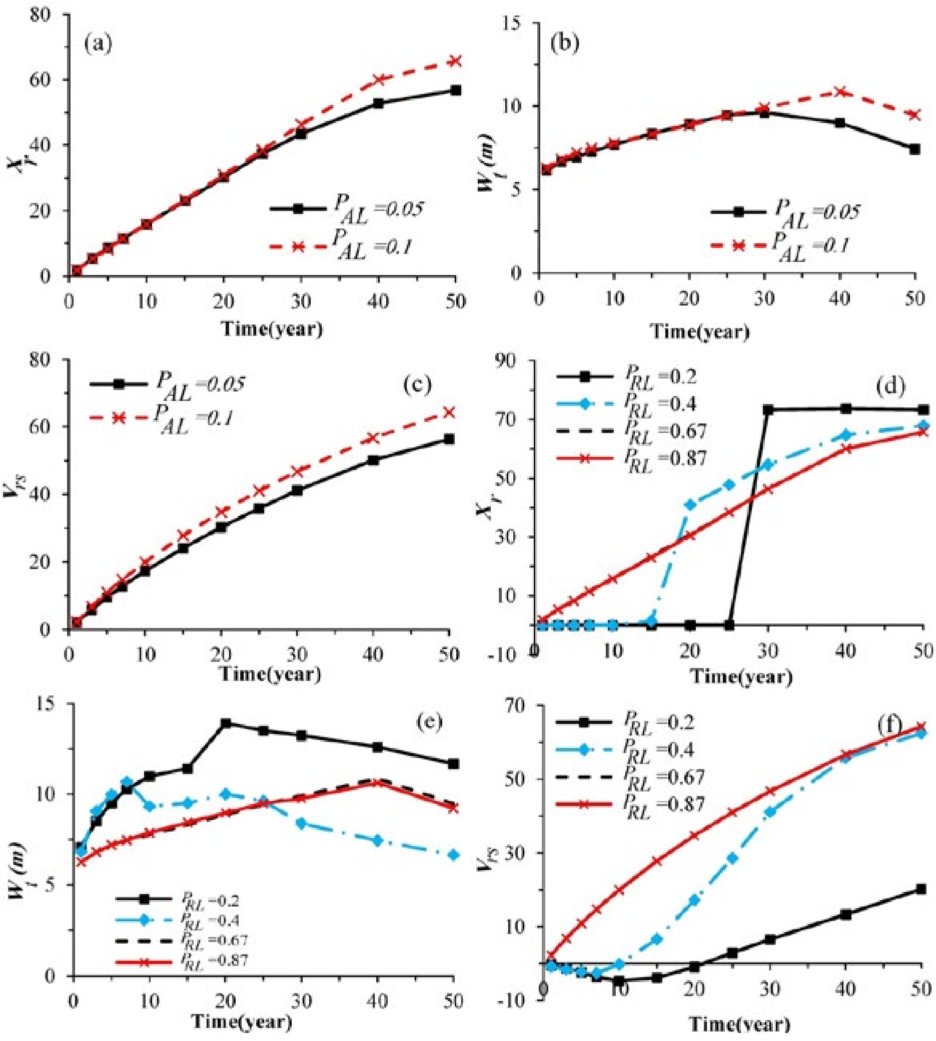

Fig. 2. The ADR efficiency (a), (b) and (c) for different abstraction well distance from shoreline and (d), (e) and (f) for different recharge well distance from shoreline

desalinated water, farther placement of abstracted well elevates the risk of permanent saline water to be purified. The results of scenarios 5, 6, 7 and 8 respectively with P_{RL} equal to 0.67, 0.87, 0.4 and 0.2, are shown in Fig. 2 (d), (e), (f) for different recharge well distance from the shoreline. The recharge wells in scenario 7 and 8 are placed at the inside of the salt wedge. It is observed that the adjacency of recharge well and the shoreline disconnects a big part of seawater from the sea. The injected freshwater between two separated saline water moves upward significantly instead of lateral, due to density-driven flow phenomenon. This creates a broad mixing zone as long as the trapped saline water is gradually faded (see the blue line in Fig. 2(e) for scenario 7). Hence, in general, effective seawater repulsion is achieved when freshwater is injected at the outside of the saltwater wedge. The ADR efficiency is almost the same for two outside recharge well scenarios with different distance to toe position but with equal

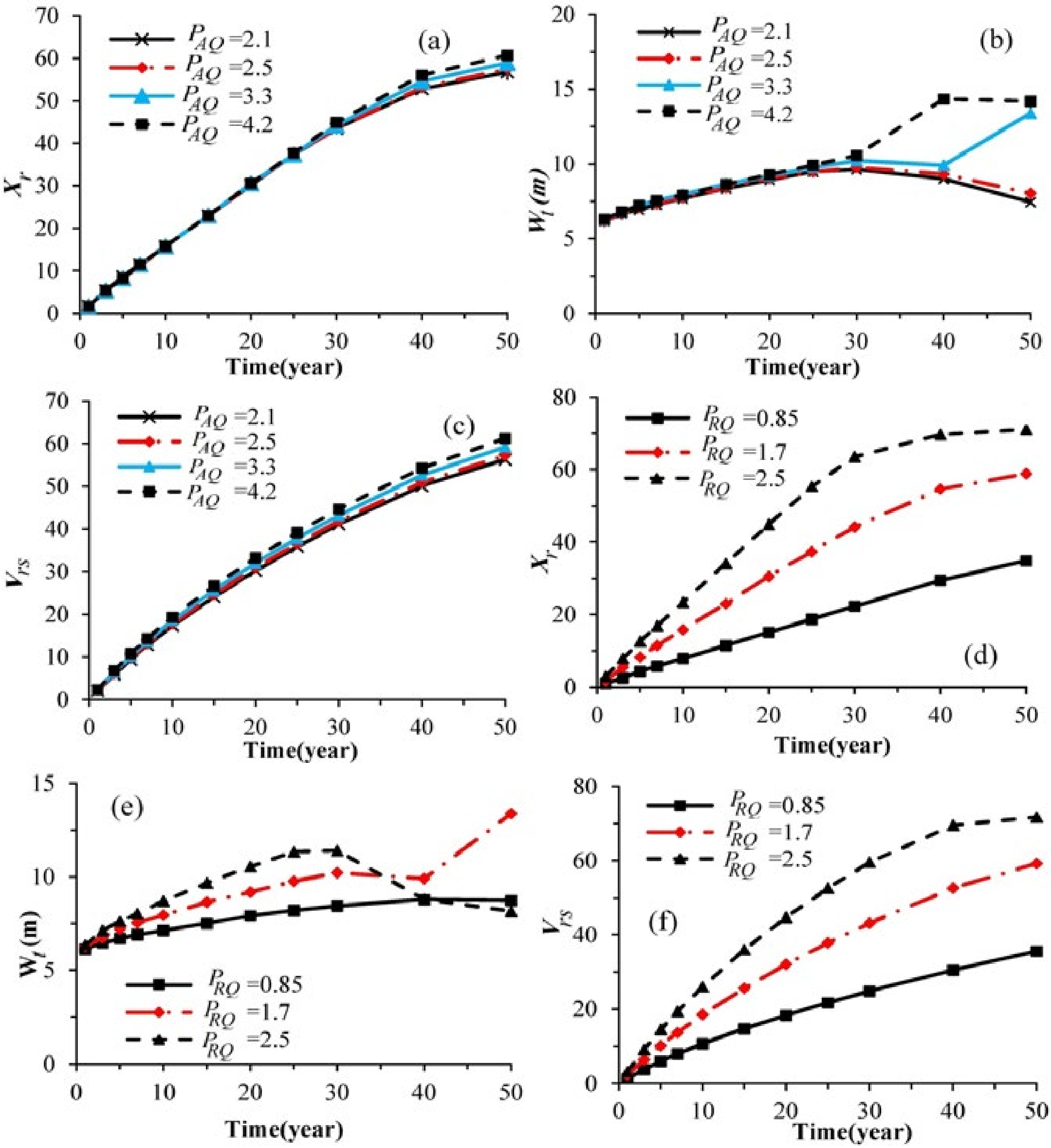

Fig. 3. The ADR efficiency (a), (b), (c) for different abstraction rate and (d), (e) and (f) for different recharge rate

recharge rate (i.e. scenario 5 and 6). This could be attributed to the velocity magnitude of injected freshwater. It is found that, the vertical component velocity of injected freshwater flow is almost equal around recharge wells in these two scenarios, but farther well gets more pulse from land boundary and has bigger horizontal velocity component. Therefore, it can compensate its farther distance.

The adjacency of abstraction well and recharge well was noticed beneficial for ADR because the salt wedge is more receded at early times of simulation. However, in regards to the radius of influence (R_e) of both wells, if the distance between the two wells is shorter than R_e, some of injected freshwater from neighbouring well may appear at abstraction well. That reduces the ADR efficiency.

Rate of abstraction and recharge

Fig. 3 (a), (b) and (c) present the sensitivity of ADR efficiency to different abstraction rates. For scenarios

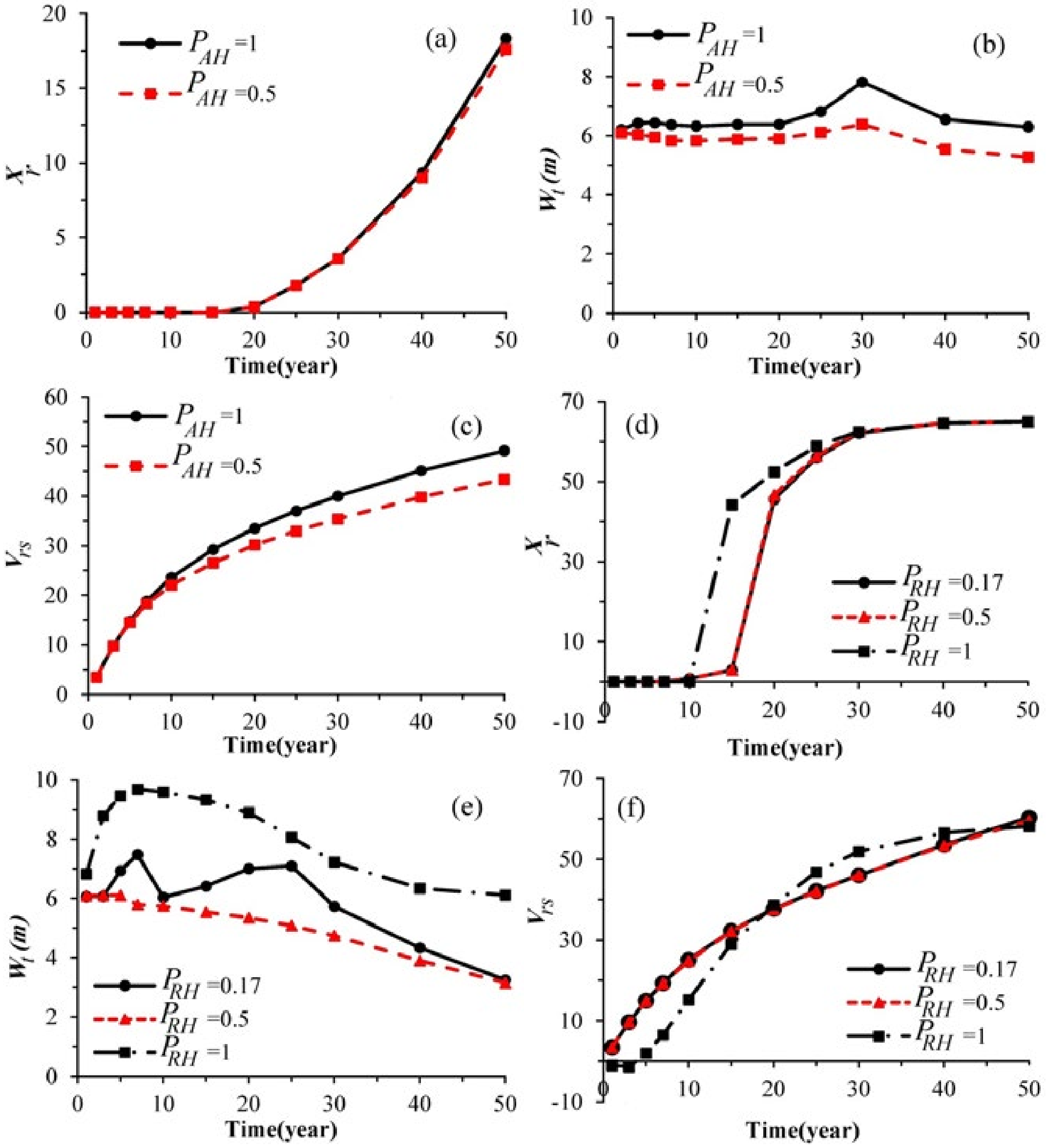

Fig. 4. The ADR efficiency (a), (b), (c) for different depth of abstraction well and (d), (e) and (f) for different depth of recharge well

2, 4, 9, 10, the P_{AQ} values obtained equal to 2.1, 3.3, 2.5 and 4.2, respectively. It is found that the increase of abstraction rate does not have particular impact on seawater recession. This is because of the nature of seawater flow to maintain the equilibrium condition. As more seawater extracted from the well, more seawater departs from the sea and replaces the abstracted saline water in the aquifer. However, as the abstraction well gets farther from sea, the salt wedge repulsion is more obvious as discussed in the previous section. The results of scenarios 1, 3 and 4 with P_{RQ} of 0.85, 2.5 and 1.7, respectively, representing different rates of recharge well are shown in Fig. 3 (d), (e) and (f). These figures demonstrate that the increase of

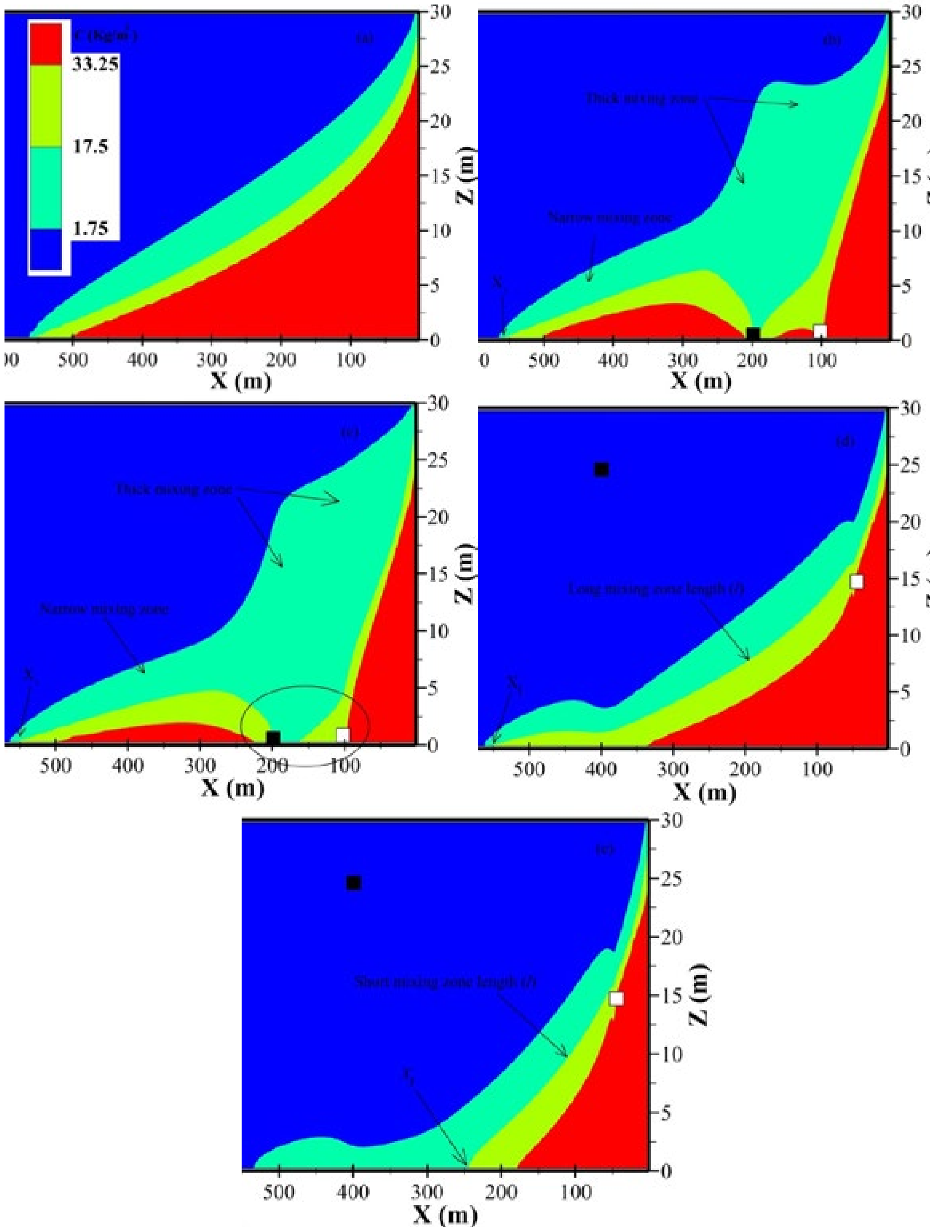

Fig. 5. (a) steady state SWI before ADR, (b), (c) respectively after 10 and 20 years of transient ADR modeling of scenario 8, (d) and (e) respectively after 10 and 25 years of transient ADR modeling of scenario 15. Solid black and white rectangular indicate recharge and abstraction wells respectively

recharge rate causes significant improvement of SWI repulsion (i.e. the V_{rs} values obtained are 36%, 59% and 72% respectively for scenarios 1, 3 and 4). The injected freshwater elevates the groundwater level in the inland site. More injected freshwater leads to higher groundwater level and consequently means higher hydraulic gradient towards the sea. For instance, the head value was 30.86 m at land boundary under steady-state condition. After 50 years of transient simulation of applying ADR, the land boundary head changed to 31.04, 31.46 and 31.24 m for 1, 3 and 4 scenarios, respectively. Higher hydraulic gradient at scenario 3 leads to better performance of ADR method in combating SWI.

Depth of abstraction and recharge well

Fig. 4 (a), (b) and (c) show the effect of different abstraction well's depth on ADR performance. For scenarios 12 and 13, the P_{AH} values obtained equal to 1.0 and 0.5 respectively. It is shown that better result is observed when the well is placed deeper into aquifer. This could be attributed to shorter distance to toe position and more access to seawater according to R_e for deep abstraction scenarios. The sensitivity of ADR efficiency to different recharge well depth is presented in Fig. 4 (d), (e) and (f). The graphs are the results of modelling scenarios 11, 14 and 15 with P_{RH} values of 1.0, 0.5 and 0.17 respectively. It is found that inserting the recharge well close to the aquifer bottom has slightly improved the ADR performance. An unstable condition occurs when freshwater is recharged deep into aquifer because freshwater with lower density is overlaid by the denser seawater. This unbalanced condition immediately converts to a stable condition as freshwater moves upward to upper layers.

Among V_{rs}, X_r and W_t that are presented in Figs. 2, 3 and 4, W_t values showed sharp variations especially for scenario 8 and 15 presented in Fig. 2 (f) and 4 (e), respectively. It is found that dilution of saline water with recharged freshwater tends to widen the mixing zone, at least at initial times. Simultaneously, salt wedge recedes toward the sea and gradually fades. These two phenomena have direct impact on mixing zone area (A_t) and its length (L_t), which makes W_t to behave irregularly. In cases where recharge well is placed at the inside of the salt wedge, the irregularity and scattered shape of mixing zone is more obvious as freshwater divided the salt wedge into two parts, land and seaside parts, and it is infeasible to compute W_t as a unique shape. To clarify the concept, SWI is depicted for two consecutive times of scenarios 8 and 15 in Fig. 5. The final extent of W_t under steady-state condition before ADR implementation was 6.1 m. According to Fig. 5 (b), after 10 years of scenario 8 modelling, wide mixing zone is formed around the recharge well while the mixing zone is narrower around the salt wedge toe. The measured W_t was 11.0 m at this time. Then while the thick mixing zone is gradually damped, the salt wedge is divided into two pieces, the L_t (i.e. the sum of two individual lengths) is reduced and consequently the magnitude of W_t increases to 13.9 m (Fig. 5 (c)). For scenario 15, after 10 years of simulation, the mixing zone had long L_t but gradually the length is shortening (Fig. 5 (e)) because X_t is receded. That led to the increase of W_t from 6.0 m to 7.1 m.

CONCLUSION

Encroachment of seawater into coastal aquifers has become a critical issue for regions where groundwater constitutes the main source of water supply. In this study, the mechanism of ADR method (i.e. Abstraction, Desalination and Recharge) to control seawater intrusion (SWI) is investigated. To understand the influence of involved parameters (i.e. abstraction and recharge rate, abstraction and recharge well distance from shoreline, abstraction and recharge well depth) on transient volume of freshwater, mixing zone thickness and salt wedge toe retreat, a hypothetical large-scale unconfined aquifer is selected. Simulations are carried out in transient mode by SEAWAT dispersive code. It is found that the change in depth of abstraction and recharge well when they are not in proximity of salt wedge toe has a minimum effect on the ADR efficiency. That is due to upward movement of freshwater with lower density. It is shown that increasing abstraction well's distance from the shoreline increased the ADR efficiency. However, the distance is subjected to some limitations (e.g. the higher cost for water conveyance). Abstraction well should not be too close to recharge well and could not be out of the salt wedge. For effective seawater repulsion, recharge well should be drilled at the outside of the saltwater wedge and close to its toe position. It is finally demonstrated that broad and irregular mixing zone may form after freshwater recharge in scenarios where recharge well is situated inside the salt wedge or the recession progress occurs rapidly. Further researches are required for real aquifers about the needed time for ADR method to be effective. Cost analysis should also be undertaken to ascertain the competitiveness of the method in comparison to other available techniques.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. In addition, the ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy have been completely observed by the authors.

ABBREVIATIONS

ADR	Abstraction, desalination and recharge
A_t [L^2]	Mixing zone area
C [M/L^3]	Saline water concentration
C_0 [M/L^3]	Seawater concentration
D_A [L]	Abstraction well depth
D_R [L]	Recharge well depth
H	Aquifer height
h_{s0}	Seawater initial head
K (L/T)	Hydraulic conductivity
L	Length scale
L_A[L]	Abstraction well distance from shoreline
L_{aq}	Aquifer length
L_R [L]	Recharge well distance from shoreline
L_t [L]	Mixing zone length
M	Mass scale
n	Porosity
P_{AH}	Dimensionless parameter of abstraction well depth
P_{AL}	Dimensionless parameter of abstraction well distance
P_{AQ}	Dimensionless parameter of abstraction rate
P_e	Peclet number
P_{RH}	Dimensionless parameter of recharge well depth
P_{RL}	Dimensionless parameter of recharge well distance
P_{RQ}	Dimensionless parameter of recharge rate
Q_A [L^3/T]	Abstraction rate
Q_{in} (L^3/T)	Freshwater inflow
Q_R [L^3/T]	Recharge rate
R (L/T)	Rainfall recharge
R_e [L]	Radius of influence
S_s [L^{-1}]	Specific storage
S_y	Specific yield
SWI	Seawater intrusion
T	Time scale
TW	Treated wastewater
V_{rs}	Dimensionless parameter of saline water volume
V_s [L^3]	Saline water volume
V_{s0} [L^3]	Steady-state saline volume extent
W_t [L]	Average mixing zone thickness
X_r	Dimensionless parameter of toe position
X_t [L]	Salt wedge toe position
X_{t0} [L]	Steady-state salt wedge toe position
α_L (L)	Longitudinal dispersivity
α_T (L)	Transverse dispersivity
Δx (L)	Cell size in x direction
Δz (L)	Cell size in z direction
ρ_f (M/L^3)	Freshwater density
ρ_s (M/L^3)	Seawater density

REFERENCES

Abd-Elhamid, H.F.; Javadi, A.A., (2011). A cost-effective method to control seawater intrusion in coastal aquifers, Water Resour. Manage., 25(11): 2755-2780 (**26 pages**).

Badaruddin, S.; Werner, A.D.; Morgan, L.K., (2015). Water table salinization due to seawater intrusion, Water Resour. Res., 51(10): 8397–8408 (**12 pages**).

Badaruddin, S.; Werner, A.D.; Morgan L.K., (2017). Characteristics of active seawater intrusion., J. Hydrol., 551: 632-647 (18 pages).

Bear, J.; Cheng, A.H.D.; Sorek, S.; Ouazar, D.; Herrera, I., (1999). Seawater intrusion in coastal aquifers: concepts, methods and practices, Kluwer, Dordrecht, The Netherlands., (**625 pages**).

Cheng, A.H.D.; Halhal, D.; Naji, A.; Ouazar, D., (2000). Pumping optimization in saltwater-intruded coastal aquifers, Water Resour. Res., 36(8): 2155-2165(**11 pages**).

Diersch, H.J.G.; Kolditz, O., (2002). Variable-density flow and transport in porous media: approaches and challenges, Adv. Water Resour., 25(8), 899-944. (**6 pages**).

Goswami, R.R.; Clement, T.P., (2007). Laboratory-scale investigation of saltwater intrusion dynamics, Water Resour. Res., 43(4): W04418, (**11 pages**).

Harbaugh, A.W., (2005). MODFLOW-2005, the U. S. Geological Survey modular ground water model- the ground-water flow process, U. S. Geological Survey Techniques and Methods, Book 6, Chapter A16, Reston, Virginia, (**253 pages**).

Javadi, A.A.; Hussain, M.; Sherif, M.; Farmani, R., (2015). Multi-objective optimization of different management scenarios to control seawater intrusion in coastal aquifers, Water Resour. Manag., 29(6): 1843-1857 (**15 pages**).

Kaleris, V.K.; Ziogas, A.I., (2013). The effect of cutoff walls on saltwater intrusion and groundwater extraction in coastal aquifers, J. Hydrol., 476: 370-383 (**14 pages**).

Ketabchi, H.; Ataie-Ashtiani, B., (2015). Review: Coastal groundwater optimization- advances, challenges and practical solutions, Hydrogeology J., 23(6):1129-1154 (**26 pages**).

Langevin, C.D.; Thorne, D.T.; Dausman, A.M.; Sukop, M.C.; Guo, W., (2008). SEAWAT Version 4: A computer program for simulation of multi-species solute and heat transport: U.S. Geological Survey Techniques and Methods, Book 6, Chap. A22, (**48 pages**).

Lu, C.; Chen, Y.; Zhang, C.; Luo, J., (2013). Steady-state freshwater–seawater mixing zone in stratified coastal aquifers, J. Hydrol., 505: 24-34 (**11 pages**).

Lu, C.; Shi, W.; Xin, P.; Wu, J.; Werner, A.D., (2017). Replenishing an unconfined coastal aquifer to control seawater intrusion: Injection or infiltration?, Water Resour. Res., 53(6), 4775-4786 (**12 pages**).

Luyun, J.R.; Momii, K.; Nakagawa, K., (2011). Effects of recharge wells and flow barriers on seawater intrusion, Ground Water, 49 (2): 239–249 (**11 pages**).

Mantoglou, A., (2003). Pumping management of coastal aquifers using analytical models of saltwater intrusion, Water Resour. Res., 39(12): 1335, (**12 pages**).

Mantoglou, A.; Papantoniou, M.; Giannoulopoulos, P., (2004). Management of coastal aquifers based on nonlinear optimization and evolutionary algorithms, J. Hydrol., 297: 209-228 (**20 pages**).

Mantoglou, A.; Papantoniou, M., (2008). Optimal design of pumping networks in coastal aquifers using sharp interface models, J. Hydrol., 361: 52-63 (**12 pages**).

Mehdizadeh, S.S.; Werner, A.D.; Vafaie, F.; Badaruddin, S., (2014). Vertical leakage in sharp-interface seawater intrusion models of layered coastal aquifers, J. Hydrol., 519:1097–1107 (**11 pages**).

Morgan, L.K.; Stoeckl, L.; Werner, A.D.; Post, V.E.A., (2013). An assessment of seawater intrusion overshoot using physical and numerical modeling, Water Resour. Res., 49: 6522-6526 (**26 pages**).

Moustadraf, J.; Razack, M.; Sinan, M., (2008). Evaluation of the impacts of climate changes on the coastal Chaouia aquifer, Morocco, using numerical modeling. Hydrogeol. J., 16: 1411-1426 (**16 pages**).

Park, N.; Cui, L.; Shi, L., (2009). Analytical design curves to maximize pumping or minimize injection in coastal aquifers, Ground Water, 47(6): 797-805 (**9 pages**).

Pool, M.; Carrera, J., (2011). A correction factor to account for mixing in Ghyben-Herzberg and critical pumping rate approximations of seawater intrusion in coastal aquifers. Water Resour. Res., 47(5), (**9 pages**).

Post, V.E.A.; Vandenbohede, A.; Werner, A.D.; Teubner, M.D., (2013. Groundwater ages in coastal aquifers, Adv. Water Resour., 57: 1-11 (**12 pages**).

Shi, w.; Lu, C.; Ye, Y.; Wu, J.; Li, L.; Luo, J., (2018). Assessment of the impact of sea-level rise on steady-state seawater intrusion in a layered coastal aquifer, J. Hydrol., 563: 851-862 (**12 pages**).

Shi, L.; Cui, L.; Park, N.; Huyakorn, P.S., (2011). Applicability of a sharp-interface model for estimating steady-state salinity at pumping wells-validation against sand tank experiments, J. Contam. Hydrol., 124: 35-42 (**8 pages**).

Todd, D.; Mays, L., (2005). Groundwater Hydrology, John Wiley and Sons, Inc. Third Ed., (**656 pages**).

Voss, C.I.; Souza, W.R., (1987). Variable density flow and solute transport simulation of regional aquifers containing a narrow freshwater-seawater mixing zone, Water Resour. Res., 23(10): 1851-1866 (**16 pages**).

Werner, A.D.; Simmons, C.T., (2009). Impact of sea-level rise on seawater intrusion in coastal aquifers, Ground Water, 47(2), pp.197-204 (**8 pages**).

Werner, A.D.; Bakker, M.; Post, V.E.A.; Vandenbohede, A.; Lu, C.; Ataie-Ashtiani, B.; Simmons, C.T.; Barry, D.A.; (2013). Seawater intrusion processes, investigation and management: Recent advance sand future challenges, Adv. Water Resour., 51: 3-26 (**24 pages**).

Zheng, C.; Wang, P.P., (1999). MT3DMS: A modular three-dimensional multispecies transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems-documentation and user's guide, Contract report SERDP-99-1, U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi., (**220 pages**).

AUTHOR (S) BIOSKETCHES

Sadjad Mehdizadeh, S., Ph.D., Assistant Professor, Department of Civil Engineering, Central Tehran Branch, Islamic Azad University, P.O. Box 13185-768, Tehran, Iran. Email: *saj.mehdizadeh@iauctb.ac.ir*

Badaruddin, S., Ph.D., Assistant Professor, Civil Engineering Department, Politeknik Negeri Ujung Pandang, P.O. Box 90245, South Sulawesi, Indonesia. Email: *sugibadaruddin@poliupg.ac.id*

Khatibi, S., M.Sc., Department of Civil Engineering, Sharif University of Technology, Tehran, Iran. Email: *sahar.khatibi@gmail.com*

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