European Water 57: 407-412, 2017.

Mechanism of controlling seawater intrusion at coastal aquifers using subsurface barrier

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Abstract: One of cases that threaten groundwater in coastal aquifers is seawater intrusion (SWI). Inserting subsurface barrier (SB) is known as a way of preventing SWI. In this study, we attempted to achieve the optimum indexes for SB characteristics including its position, height, thickness and hydraulic conductivity. Numerous scenarios have been defined and the finite difference dispersive SEAWAT model has been used. The positive impact of SB is evaluated by measuring the salt wedge toe retrogression, freshwater volume increase and the reduction of trapped salt wedge dimension over time. The results indicated that inserting the SB closer to shoreline control the SWI more efficient due to dilution of larger trapped wedge behind it. The results also illustrated that the more the height of SB approaches to 5% salinity contour the more efficient it would be. It is also shown that changing the thickness of SB had the least effect on SWI controlling but by reducing its permeability, its performance in short term and long term had an effective improvement. Therewith, analyzing the performance of SB in aquifer with presence of extraction well demonstrated that even though SB can act successfully in reducing the salinity of extracted water, it cannot eradicate it entirely. Turning over of saline flow form above the barrier and reaching the salt wedge behind it, is found to be the reason. Eventually, the results showed that constructing a SB is not a short-term method for controlling SWI and its effects are more significant in long period.

Key words: Coastal aquifer, Seawater intrusion, subsurface barrier, Transition zone

1. INTRODUCTION

Researches on controlling seawater intrusion (SWI) in coastal aquifers had a tremendous growth in the past decade but are mostly limited to all methods rather than constructing subsurface barrier (SB) (i.e. Cheng et al., 2000; Mantoglou, 2003; Mantoglou et al., 2004; Mantoglou and Papantoniou, 2008; Park et al., 2009; Abd-Elhamid and Javadi, 2011). Luyun-Jr et al. (2009) did a numerical and experimental research on controlling SWI in an unconfined coastal aquifer using SB. Based on their experiments, low height barriers can remove the salt wedge faster while the height needs to be determined properly as constructing a low height barrier might not be helpful for special cases. These researchers in 2011 investigated the effect of the recharge well and retaining walls location on salt wedge receding. Their results showed that the closer the recharge well to salt wedge, the better performance it has in removing the salt from aquifer and the further it goes, the weaker it becomes. Using a liner equation, they also proved that salt wedge would recede more when the barrier is built deeper and closer to ocean. At this study, we have distinguished the SB and retaining walls. Walls generally begin from the surface of aquifers, and it does not necessarily stretches to the bottom of the aquifer.

Kaleris and Ziogas (2013) evaluated the effects of retaining walls on saltwater dynamic movements and protecting groundwater extraction in coastal areas of Greece, based on SUTRA dispersive model. They concluded that the wall proper performance happens when the wall is constructed in a depth of more than 60% of the aquifers height and is located closer than twice the aquifer's height. They also found that constructing a retaining wall is more effective in heterogeneous aquifers and the greatest impact on SWI occurs when the hydraulic conductivity of the barrier is less than 10% of the hydraulic conductivity of the whole aquifer. Review of previous studies indicates that the SB impact on the increase or decrease rate of saltwater and freshwater volume, optimum geometrical parameters of a barrier, the flow path lines near the barrier and finally analyzing the efficiency of SB while well is pumping water, is not investigated yet. Therefore, in this study, using SEAWAT dispersive model, a two-dimensional saturated homogeneous unconfined aquifer is simulated for different position, height, thickness and hydraulic conductivity of SB to investigate reduction of salinity over times. The impact of constructing SB on thickness of transition zone is also provided in this study. Finally, the simultaneous performance of well and the barrier is investigated and the influence of the barrier on decreasing the salinity of extracted water has been analyzed.

2. MATERIALS AND METHODS

2.1 Large-scale aquifer

The chosen large-scale aquifer in this study is an unconfined, homogenous and two-dimensional aquifer that is similar to the aquifer presented by Lu et al. (2013). The simulated area, according to Figure 1, includes 430 m of landward and 70 m of seaward boundary. The height of the aquifer is 48 m and the sea section and the land section is separated by a coastal line with a 0.1 slope. The concentration of seawater in the ocean is 35 Kg/m^3 and the freshwater constant head (H_f:[L]) and seawater constant head (H_s:[L]) are respectively 46.2 and 45 m at vertical side of the aquifer. The aquifer bed assumed as no-flow boundary condition.

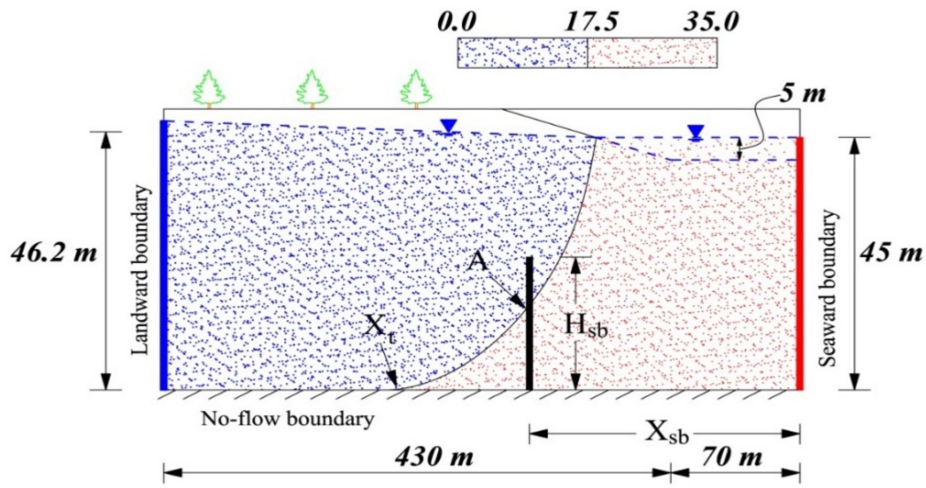

Figure 1. Dimensions and specifications of simulated aquifer

2.2 SEAWAT model settings

SEAWAT simulates SWI in aquifers by solving groundwater flow equation using MODFLOW model, and contaminant transport equation using MT3DMS model. The governing equations of groundwater flow and contaminants can be found in many recent studies (e.g. Langevin et al., 2008) and it is not expressed here for brevity. The aquifer is assumed homogenous, isotropic, and hydraulic conductivity equals to 8.64 m/d. Porosity is set to 0.4 for each cell and the longitudinal dispersivity is considered 1 m through aquifer. The cell dimensions are assumed 1.0 m in length (ΔX) and 0.5 m in height (ΔZ). The model is first simulated for sufficiently long time to reach to steady condition. Then the SB is placed at desired location and the aquifer is simulated for 85 years at transient state. Specific yield (S_y) and specific storage (S_s) is respectively 0.25 and 0.0008 m^{-1} and time steps are set to 5 days for both flow and transport equations.

14 different scenarios are defined which are similar in time, boundary and initial conditions but differ at SB specifications. These specifications include (1) the distance between SB and the ocean (X_{sb}), (2) the height of SB (H_{sb}), (3) its width (W_{sb}) and (4) its hydraulic conductivity (K_{sb}). These specifications became dimensionless by dividing them with length and height of the aquifer according to Table 1. The average groundwater level is chosen as the height of the aquifer (H: [L]).

Table 1. Specifications of simulated scenarios

Scenario	Ksb (m/d)	Kr:Ksb/Kh	Wsb (m)	Wr:Wsb/H	Hsb (m)	Hr: Hsb/H	Xsb (m)	Xr:Xsb/L
Ts-1	0.00864	0.001	2	0.04	23.5	0.52	203	0.41
Ts-2	0.00864	0.001	2	0.04	23.5	0.52	248	0.50
Ts-3	0.00864	0.001	2	0.04	23.5	0.52	303	0.61
Ts-4	0.00864	0.001	2	0.04	12.5	0.27	248	0.50
Ts-5	0.00864	0.001	2	0.04	18.5	0.41	248	0.50
Ts-6	0.00864	0.001	2	0.04	22.5	0.49	248	0.50
Ts-7	0.00864	0.001	4	0.09	22.5	0.49	248	0.50
Ts-8	0.00864	0.001	6	0.13	22.5	0.49	248	0.50
Ts-9	0.0864	0.010	2	0.04	22.5	0.49	248	0.50
Ts-10	0.000864	0.0001	2	0.04	22.5	0.49	248	0.50
Ts-11	0.08640	0.010	2	0.04	12.5	0.27	294	0.59
Ts-12	0.00864	0.001	4	0.09	12.5	0.27	248	0.50
Ts-13	0.00864	0.001	4	0.09	17.5	0.38	248	0.50
Ts-14	0.00864	0.001	2	0.04	12.5	0.27	294	0.59

2.3 The methods of scenarios comparison

In most of recent studies on SWI problem, the thickness of transition zone is used according to following equation:

$$\mathrm{W_t} = \frac{\mathrm{A_t}}{\mathrm{L_t}} \tag{1}$$

where W_t indicates the thickness of the zone [L], A_t indicates its area [L^2] and L_t indicates the length of it [L]. Considering 5% to 95% of sweater as transition zone threshold, this area will gradually decrease due to dilution over time by freshwater. The shape of the transition zone over time demonstrates that because of drastic changes and the irregularity of its area behind the barrier, W_t cannot be an appropriate index to compare the scenarios. In this study, the receding rate of salt wedge toe (X_t: [L]) and the height reduction of the trapped salt wedge (A: [L], see Figure 1) with $0.5C_s$ criterion (C_s: sea salinity concentration) are two selected indexes for investigating SWI that have been dimensionless, using the following equations:

$$\mathrm{RR} = 100\times\left(\frac{\mathrm{X_{t0}}-\mathrm{X_{ti}}}{\mathrm{X_{t0}}}\right) \tag{2}$$

$$\mathrm{A_r} = 100\times\left(\frac{\mathrm{A_0}-\mathrm{A_i}}{\mathrm{A_0}}\right) \tag{3}$$

where X_{t0} is the length of salt wedge toe before construction of SB, X_{ti} is the length of salt wedge toe at time i. RR is the receding percentage of salt wedge toe at the same time, A_0 is the height of $0.5C_s$ salinity contour before construction of the barrier at its position. A_i is the similar height at time i and finally A_r is the decrease percentage of mentioned height.

3. RESULTS AND DISCUSSION

3.1 Longitudinal distance of SB from sea

Three scenarios including Ts-1 (the barrier is located at right one-third side of the transition zone), Ts-2 (the barrier is located at the middle of the transition zone) and Ts-3 (the barrier is located at left one-third side of the transition zone) are evaluated in this section according to Figure 2.

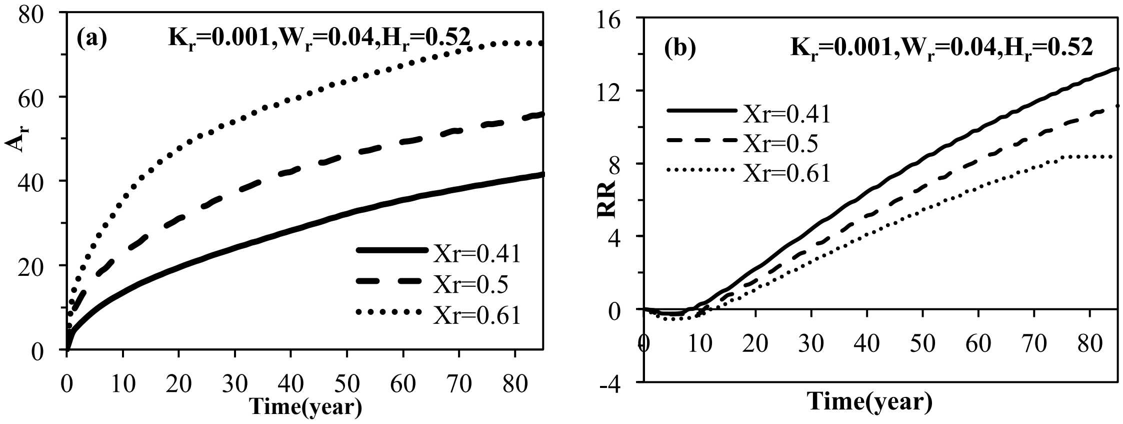

Figure 2. The impact of different longitudinal location of SB on (a) A_r and (b) RR dimensionless parameters

According to above comparison, in terms of SB distance from coastline, the closer the SB is to the ocean, the better performance achieved both in long-term and short-term. However, by constructing the barrier closer to the ocean, the W_t will not decrease. The W_t was 8.5, 8.1 and 6.9 m after 85 years as respectively SB getting further from ocean. The thicker transition zone for closest SB scenario to coastline is not a disadvantage as more dilution of the salt wedge that is trapped behind the barrier occurs at this scenario.

3.2 Optimal height of SB

Considering the fact that the aim of constructing a SB is to protect the aquifer against SWI with concentrations more than 1.75 kg/m^3, the H_{sb} is defined for Ts-6, Ts-5 and Ts-4 scenarios respectively lower, same and higher than 1.75 kg/m^3 salinity contour height at the location of barrier. Scenarios Ts-12 and Ts-13 follow the same rules and H_{sb} is respectively less and equal to 1.75 kg/m^3 salinity contour but the SB is thicker in these two scenarios.

According to Figure 3, increasing H_{sb}, disconnects the seawater flow available in front and behind of the barrier and consequently leads to severe reduction of A point height. This condition is partly true for salt wedge receding rate and the scenarios with higher H_{sb} performed better. Before constructing the SB, the saltwater flow direction is first toward the transition zone and then turns toward the sea. By constructing the barrier, saltwater flow near the salt wedge toe still tends to turn toward the sea. However, by increasing the barrier's height, the trapped brackish flow behind the barrier starts to spin as they contacted the barrier and finally they are obliged to pass a longer path in order to reach the ocean. The velocity reduction and flow slow motion results in larger salt plume behind the SB and occupies a larger area of the aquifer at initial years.

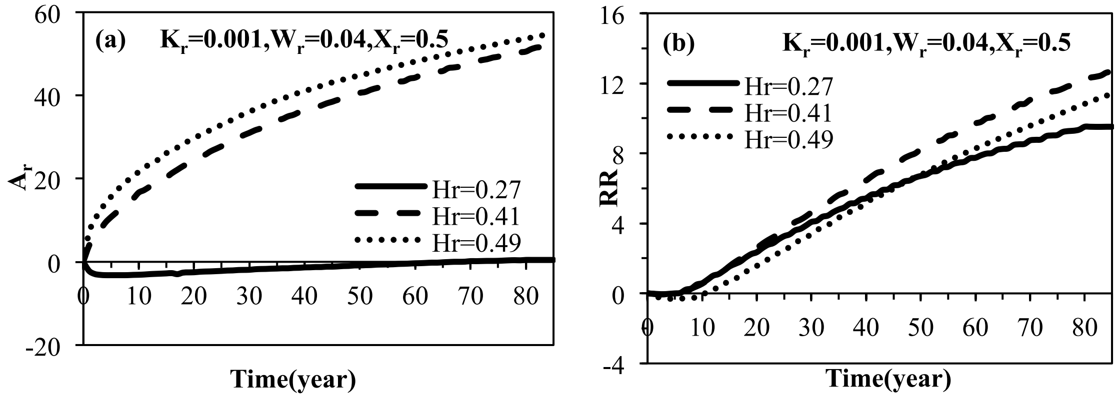

Figure 3. The effect of different H_{sb} on (a), A_r and (b) RR dimensionless parameters

3.3 Thickness and hydraulic conductivity of SB

There is no tangible difference in barrier performance when W_{sb} is changed. Obviously, the thicker SB could potentially provide better results but its requirement of more space than the narrow ones can slightly reduce the freshwater volume. It is clear that the less permeable scenarios are significantly more successful. Increasing or decreasing K_{sb} has a direct impact on flow transmission through the barrier body and leakage across the body of barrier diminishes its efficiency.

3.4 The influence of SB on improving salinity of extracted water

Since one of the main goal of constructing SB is improving the quality of extracted water, in the last part of this study the salinity of arbitrary placed well is measured for selected scenarios. For real similarity, both fully and partially penetrated well are modeled. It is found that the salinity of abstracted water has decreased considerably specially for fully penetrated well as it gets closer to coastline. The salinity changed from 9.8 kg/m^3 to 2.7 kg/m^3 (i.e. 72% decay rate) after ten years for fully penetrated case. Nonetheless, the progress has stopped after almost ten years and SB could not completely convert the extracted brackish water to freshwater. Similar desalinated trend occurred for water of partially penetrated well but slower than the fully penetrated scenario. The partially penetrated well had initially 1.1 kg/m^3 salinity but after 10 and 85 years, respectively it reduced with 27% and 92% decay rate.

4. CONCLUSION

SB is known recently an effective solution to prevent SWI. In this study, dispersive SEAWAT model is used to introduce optimum parameters for SB including longitudinal position, barrier height, thickness and its hydraulic conductivity. The simulated large-scale aquifer is assumed two-dimensional homogeneous aquifer. The simulation results demonstrated that constructing SB widens the transition zone. That is because of SB that prevents routine movement of saline water around toe position to be discharged to the sea. The flow velocity consequently reduces around the toe and eventually leads to diffused flow directions. It is also found that inserting SB closer to shoreline controls SWI more efficiently. That is due to greater trapped saline water behind the SB lost its connection with sea and gradually is diluted by freshwater. The results also indicate that if the height of SB approaches to 5% concentration contour line and if it was shorter from this contour respectively in long and short time more efficient SWI controlling will be achieved. Higher SB increases mixing zone thickness at early times. It is shown that changing thickness of SB has the minimum effect on SWI controlling but generally more thickness leads to better SWI controlling. It is concluded that as the hydraulic conductivity decreased, the operation of SB is improved due to major disconnection of flows at both side of SB. Constructing SB improves the salinity of abstracted water too. It is found that proximity of well and SB pulls seawater toward well screen and cannot completely retard the trapped salt wedge. It is finally advised that constructing SB should be considered as long-term remediation activity for aquifers expose to SWI.

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