



An alternative approach to control saltwater intrusion in coastal aquifers using a freshwater surface recharge canal

Mahdi Motallebian^{a,*}, Hojjat Ahmadi^{a,b}, Amir Raoof^c, Nick Cartwright^d

^a Urmia University, Department of Water Engineering, Urmia, Iran

^b Urmia Lake Research Institute, Urmia, Iran

^c Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands

^d Griffith University, Gold Coast, Australia

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ABSTRACT

Aquifers are a major source of freshwater in many parts of the world. Saltwater intrusion from the sea or saline lakes into freshwater aquifers degrades the potable quality of these resources. Various methods have been introduced to mitigate saltwater intrusion, such as recharge wells and physical subsurface barriers. This paper presents an alternative approach to control saltwater intrusion in coastal aquifers using a surface water recharge canal. In this paper, the effectiveness of a recharge canal at mitigating saltwater intrusion is evaluated numerically using SEAWAT. The results indicate that the recharge canal leads to a reduction in the extent of the saltwater intrusion. Under a fixed hydraulic gradient, the extent of this reduction is dependent on the location of the recharge canal relative to the saltwater source. As the hydraulic gradient increases, with the optimum location of the recharge canal approaches the saltwater source location. The results also indicate that more effective saltwater repulsion is achieved when the recharge canal is located near the toe of the saltwater wedge. The results of a field scale case study indicate that a recharge canal with relatively small dimensions could have a significant effect on reduction in the extent of the saltwater intrusion.

1. Introduction

Saltwater intrusion (SWI) is a serious environmental issue since 80% of the world's population live along the coast and utilize local aquifers for their water supply (Barlow, 2000). Globally, coastal aquifers are under threat from saltwater intrusion (SWI). SWI is caused by changes in coastal aquifer conditions resulting from ground water extraction, climate drivers, sea-level rise, oceanic over topping events, and land use change (Sebben et al., 2015). Under natural conditions, these coastal aquifers are recharged by rainfall events, and the regional groundwater flow towards the ocean counters the intrusion of saltwater into the freshwater region. However, over-exploitation of coastal aquifers in some regions has resulted in a reduction in fresh groundwater levels (and hence reduced natural flow) and this has led to an increase in saltwater intrusion. Saltwater intrusion degrades the quality of coastal aquifer groundwater resource which can lead to a reduction in crop yield efficiency, limitation on the drinking water resource as well as soil fertility and salinity of operated wells. Such problems are more crucial where groundwater aquifers are shallow. In arid and semi-arid regions,

low precipitation limits groundwater recharge and therefore leads to drying of aquifers (Custodio and Bruggeman, 1987).

Spatial variation of water density can lead to variable-density flow, which is a key process in the transport of contaminants, salt transport in coastal aquifers or hot geothermal plumes (Cremer and Graf, 2015). Coastal aquifers are complex physical systems because (i) two different water types, freshwater and seawater, coexist, (ii) time scales at which hydraulic processes occur are different for the seaside and the landside, and (iii) many physical processes control coastal flow dynamics, such as variably saturated flow, variable-density flow, salt transport, storm surge and subsequent infiltration of saltwater, evaporation and precipitation, and periodically submerged coastal areas (Yang et al., 2013). In addition, natural extreme events such as tsunami and coastal storms may exacerbate saltwater intrusion and cause contamination of a large volume of fresh water (Illangasekare et al., 2006). van Lopik et al. (2015) focused on salinization of some aquifers based on thermodynamics effects of oil well and drilling rigs and they also used SEAWAT as numerical model. They informed that the transferred heat from operated oil wells to aquifer affected on density of saline water

* Corresponding author.

E-mail addresses: m.motallebian@gmail.com (M. Motallebian), hojjat.a@gmail.com (H. Ahmadi), a.raoof@uu.nl (A. Raoof), n.cartwright@griffith.edu.au (N. Cartwright).

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and consequently the flow pattern of associated streams as well the interfere of lower saline water with upper fresh water.

The management of coastal settings, in which the construction and operation of pumping wells is a key factor, should adopt quantitative measures of the SUZI (Saltwater upconing zone of influence) extent to account for the salinity implications, arising from enhanced salt-water upconing, on neighboring wells (Jakovic et al., 2016). The management of the water supply systems that use groundwater from coastal aquifers that are subjected to saline water contamination is a complex task. Such management models at different levels of success have been reported in the literature (Shamir et al., 1984; Finney et al., 1992; Emch, 1996; Nishikawa, 1998; Benhachmi et al., 2003). Advantages of groundwater recharge by surface spreading include: (a) groundwater supplies may be replenished in the vicinity of metropolitan and agricultural areas where groundwater over-drafting is, and (b) surface spreading provides the added benefits of the treatment effect of soils and transporting facilities of aquifers (Asano and Cotruvo, 2004). The protection and management of freshwater lenses in coastal aquifers (barrier islands, atolls) is of great interest because they appear worldwide (Vithanage et al., 2012). Therefore, understanding the dynamics of salt–fresh water interaction is essential to assist in developing mitigation strategies. Several strategies have been proposed to prevent or minimize saltwater intrusion in coastal aquifers (e.g. Todd, 1959; Oude Essink, 2001). These may be summarized into the following methods: (1) reduction or rearrangement of the pattern of groundwater extraction; (2) artificial recharge from spreading basins or recharge wells; (3) development of a pumping trough by saltwater extraction adjacent to the coast; (4) maintenance of a freshwater ridge by freshwater injection along the coast; (5) construction of artificial subsurface barriers; and (6) land reclamation.

Da Silva and Haie (2007) investigated optimal locations of groundwater extractions in coastal aquifers, the results showed different domain variables and their non-linear behavior. Locations were analyzed as a function of groundwater withdrawal and security distance. The maximum allowable extraction and the distance between the toe of the interface and the control point before invasion were studied for each eventual location. It was found that the security of water resources systems can be reasonably increased by a small inward move of the location of the wells. Narayan et al. (2003) studied effects of groundwater pumping on Saltwater intrusion in the lower burdekin delta, north Queensland and the results showed that the saltwater intrusion is far more sensitive to pumping rates and recharge than aquifer properties such as hydraulic conductivity. Sherif and Hamza (2001) performed Simulations in the vertical view and equipotential lines were plotted for different locations of brackish water pumping. In all of the tested runs, the width of the dispersion zone has reduced significantly due to brackish water pumping. The quality of the pumped water differs according to the location of pumping.

Luyun Jr et al. (2009) investigated the effectiveness of a cut off wall to mitigate the salt-water intrusion problem using a sandbox with dimensions of $90 \times 60 \times 8$ cm (length, height and width respectively) and a SEAWAT numerical model to study additional configuration alternatives that were considered in the laboratory setup. Experimental and numerical results showed that a shorter cutoff wall achieved a faster removal rate of residual saltwater than a higher wall. Simulations of shorter cutoff wall heights show that a minimum height limit on the cutoff wall is needed to achieve complete removal of residual saltwater. Residual saltwater will be flushed if the wall height exceeds the thickness of the saltwater wedge at that position. Abdoulhalik and Ahmed (2017) investigated the effectiveness of cutoff walls to control saltwater intrusion in multi-layered coastal aquifers, results show that the cutoff wall was effective in reducing the saltwater wedge in all the investigated cases of layered-aquifers with toe length reduction of up to 43%. The wall exhibited more wedge reduction in shallower than steeper hydraulic gradients and presence of an underlying low permeability layer was found to obstruct the freshwater flow in the lower part

of the aquifer, thereby slowing down the velocity through the wall opening. Numerical analysis of other layering patterns of monotonically increasing/ decreasing permeability from top to bottom showed that the cutoff wall remained effective in repulsing the seawater wedge. Luyun Jr et al. (2009) studied the effects of recharge wells and flow barriers on seawater intrusion and their findings showed that more effective saltwater repulsion is achieved when the recharge water is injected at the toe of the saltwater wedge and more effective saltwater repulsion is achieved with deeper barrier penetration and with barriers located closer to the coast.

Due to an increased practical functionality and efficiency, the control of SWI with the use of hydraulic barriers has gained more popularity than the design of physical barriers as engineering interventions (Oude Essink, 2001; Pool and Carrera, 2010; Werner et al., 2013). The main types of hydraulic barriers include artificial recharge (recharge barrier), extraction of brackish or saline water along the coast (abstraction barrier) or a combination of techniques (mixed barriers). The most efficient form of mixed barrier is the simultaneous use of recharge and abstraction barriers (Abd-Elhamid and Javadi, 2011; Hussain et al., 2015). Continuous abstraction of brackish water near the coast, desalination of the abstracted brackish water for public use and simultaneous recharge of the aquifer using treated wastewater or other sources of good quality surface water (through surface infiltration basins or injection wells) have been introduced by Hussain et al. (2015) for cost-effective control of SWI in coastal aquifers. Noorabadi et al. (2017) conducted a study on the effect of groundwater extraction on the movement of saltwater wedge. They also used SEAWAT for assessment of additional scenarios. Masciopinto (2013) studied aquifer recharge in Lebanon and found that groundwater well barriers can be effective at removing seawater intrusion from fractured carbonate aquifers. Zimmermann et al. (2006) studied the salt transport on islands in the Okavango Delta, they found that density effects may be entirely overridden by lateral flow on islands embedded in a sufficiently high regional hydraulic gradient.

Aquifer management practices include large recharge pits to assist with artificial replenishment of groundwater. Artificial recharge can be used to maintain groundwater levels and subsequently control seawater intrusion (Narayan et al., 2003). All channels act as recharge areas, while in the interfluvial areas in between highly saline water is almost stagnant. Hydrologic system boundaries are therefore given by the two fault systems perpendicular to a river and the parallel water divides between adjacent river valleys (Bauer et al., 2006). the future of artificial recharge of groundwater looks extremely good as dams are losing popularity and underground storage is becoming a major alternative for overcoming short-term, seasonal, or long-term differences between water supply and demand (National Research Council, 1994). In order to preserve and to ensure a sustainable management of the groundwater resources, it is appropriate to limit in the short time groundwater pumping in the coastal areas, to delineate suitable plan for future groundwater management and to examine the possibilities of artificial recharge in the most vulnerable area to the marine intrusion (Gaaloul, 2012). Low permeability subsurface barriers consist of vertical walls (slurry walls, steel or concrete sheet piles) placed inland to block seawater intrusion that this system requires considerable engineering and investment. Moreover, it may be counterproductive if pumping stops or sources of contamination exist (Bolster et al., 2007).

As mentioned above, most studies have explored costly and hard methods, including recharge wells and underground dams, that implementation of them requires the drilling of wells, pumping stations and power stations. In this paper, we present an alternative method based on providing a hydraulic freshwater by way of a surface water recharge canal. This method is similar to other artificial recharge methods, with the difference that there is no need for digging multiple basins, digging wells, pumping stations, etc. The recharge canal approach only requires a canal to be dug along the saltwater source and the construction of a hydraulic control structure to control the canal

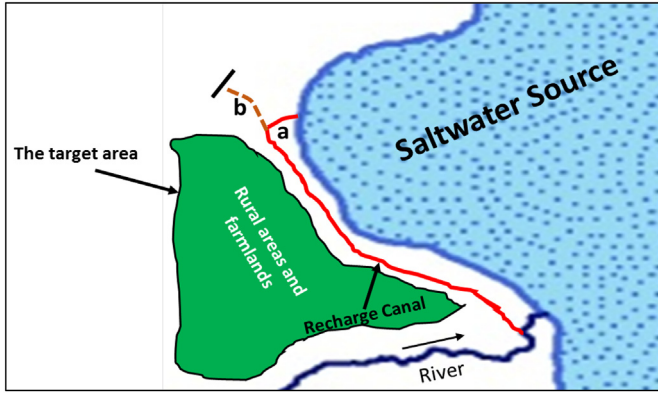


Fig. 1. Location of the recharge canal (a) connected to a saltwater source and (b) blocked at the end.

water level. Management of this method after the initial civil construction works is relatively easier than the other artificial recharge methods mentioned above as it doesn't rely on pumping. The recharge canal method proposed here aims to create a continuous hydraulic barrier around the saltwater reservoir using the freshwater head formed via recharge from the canal. In this paper, we first validate the numerical model SEAWAT against the experimental data of Goswami and Clement (2007) before conducting a parametric study on the optimal configuration of the recharge canal relative to the SWI.

2. Materials and methods

2.1. Introducing an alternative method for controlling saltwater intrusion

In the proposed recharge canal method, first, the area to be protected is determined, and then a canal with appropriate dimensions is excavated around the area and some of the natural river flow is diverted into the recharge canal. This canal can be blocked at the end or connected to the sea/ lake (Fig. 1). when the water level in a stream is higher than the water level in an adjacent (or underlying) aquifer, water will flow from the river to the aquifer (Bear and Cheng, 2010). Here, the recharge canal has been studied and analyzed based on the three scenarios:

- 1- Simulating the influence of location of recharge canal on the salt-water wedge
- 2- Determining the effect of hydraulic gradient changes on optimal location of recharge canal
- 3- Determining the effect of water table mound under the recharge canal on toe salt- wedge position

The details of the above scenarios are described in Section 2. 5.

2.2. Modelling approach

The model SEAWAT is an industry standard for modelling saltwater intrusion problems however it is limited to simulated saturated zone flows only. The influence of a surface recharge canal on the water table profile requires consideration of unsaturated flows between the recharge canal and the water table. Therefore, the adopted modelling approach was to firstly simulate the influence of the recharge canal on the water table profile using SEEP/W (cf. Section 2.2.1). The resultant water table profile was then applied as the upper boundary condition for SEAWAT (cf. Section 2.2.2) which was used to model the saltwater intrusion.

2.2.1. SEEP/W

SEEP/W is a numerical model that can mathematically simulate the

real physical process of water flowing through a particulate medium and can be applied to analyze groundwater seepage and excess pore-water pressure dissipation problems within porous materials such as soil and rock (Geo-Slope, 2012). SEEP/W has been widely used for channels and dams seepage simulations and modelling of groundwater flow (e.g. Aryafar et al., 2007; Aghvami et al., 2013; Arshad and Babar, 2014; Broaddus, 2015; Arshad et al., 2016). Its comprehensive formulation allows for one to consider analyses ranging from simple, saturated SteadyState problems to more complex, saturated/unsaturated time-dependent flow problems. SEEP/W solves the following governing equation:

$$\frac{\partial}{\partial x} \left[k_x \left(\frac{\partial h}{\partial x} \right) \right] + \frac{\partial}{\partial y} \left[k_y \left(\frac{\partial h}{\partial y} \right) \right] + Q = \frac{\partial \theta}{\partial t} \quad (1)$$

where h is hydraulic head, k_x and k_y are hydraulic conductivity in x and y directions, respectively, Q is the applied source or sink terms, t is the time domain and θ is volumetric water content.

In this study, SEEP/W was used to calculate water table mound under the recharge canal and then this water table was considered as a boundary condition for the SEAWAT model.

2.2.2. SEAWAT

SEAWAT has been widely used for saltwater intrusion numerical simulations (e.g. Chang et al., 2011; Lu and Werner, 2013; Chang and Clement, 2013; Abdoulhalik and Ahmed, 2017; Werner, 2017; Chang et al., 2018; Abdel Gawad et al., 2018). SEAWAT was specifically designed for the simulation of SI, although it has many other applications as well, notably the combined simulation of groundwater flow and heat transfer (Werner et al., 2013). SEAWAT as a widely used, three-dimensional variable-density groundwater flow and transport model has been developed by the USGS based on MODFLOW and MT3DMS and includes two additional packages: Variable-Density Flow (VDF) and Viscosity (VSC). SEAWAT solves the following density-dependent flow equation as derived by Frind (1982),

$$\begin{aligned} \frac{\partial}{\partial x} \left[\rho k_{fx} \left(\frac{\partial h_f}{\partial x} \right) \right] + \frac{\partial}{\partial y} \left[\rho k_{fy} \left(\frac{\partial h_f}{\partial y} \right) \right] + \frac{\partial}{\partial z} \left[\rho k_{fz} \left(\frac{\partial h_f}{\partial z} + \left(\frac{\rho - \rho_f}{\rho_f} \right) \frac{\partial z}{\partial t} \right) \right] \\ = \rho S_f \frac{\partial h_f}{\partial t} + \theta \frac{\partial \rho}{\partial C} \frac{\partial C}{\partial t} - \rho_s q_s \end{aligned} \quad (2)$$

where ρ [ML^{-3}] is the density of the original aquifer water, k_{fx} , k_{fy} , k_{fz} [LT^{-1}] are hydraulic conductivities in three dimensions of x , y and z respectively, S_f [L^{-1}] the specific storage in term of equivalent fresh water head, θ is the effective porosity (dimensionless), h_f [L] is the equivalent freshwater head, ρ_s [ML^{-3}] density of contaminant (salt-water), ρ_f [ML^{-3}] is the density of freshwater, q_s [T^{-1}] is in or outlet flowrate to aquifer and C [ML^{-3}] is concentration of contaminant.

For groundwater flow with large density variations in the solute transported, the redistribution of the solute concentration changes the density field itself which, in turn, affects the groundwater flow. Therefore, groundwater flow and transport of solute in the aquifer are coupled processes in such a situation, so that the flow Eq. (2) is solved jointly with the following transport equation,

$$\frac{\partial C}{\partial t} = \nabla \cdot (D \cdot \nabla C) - \nabla \cdot (qC) - \frac{q_s C_s}{\theta} + \sum_{k=1}^N R_k \quad (3)$$

where D is the hydrodynamic dispersion tensor defined as $D = D_m + D^*$, where D_m and D^* are the mechanical dispersion and pore diffusion coefficient, respectively. The former being related to the linear fluid velocity v through $D_m = f(v, A_L, A_T)$, with A_L and A_T the longitudinal and transversal dispersivity, respectively; C_s is the solute concentration of water entering from sources or sinks and R_k is the rate of solute production or decay in reaction k of N different reactions. In the present case of pure saltwater transport, R_k is set to zero.

In this study, SEAWAT was used to calculate two-dimensional

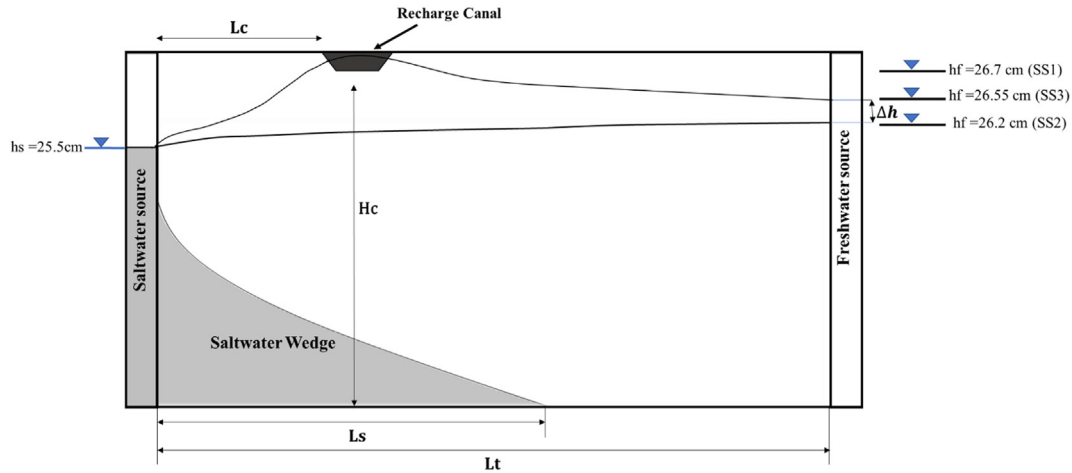


Fig. 2. Geometry, boundary conditions used in the numerical model.

variable-density groundwater flow and transport equations.

2.3. Problem definition

In this study, the experimental data of Goswami and Clement (2007) was used to validate the model before modifying the configuration to examine the ability of the recharge canal to reduce saltwater intrusion. The experimental setup consists of a rectangular domain of 53.5 cm long \times 25.5 cm high with constant-head boundary conditions at either end (freshwater at the upstream end and saltwater at the downstream end, cf. Fig. 2). The intrusion problem was investigated under the following three hydraulic gradients:

- a) SS1 - steady hydraulic gradient $i = 0.022$ ($\Delta h = 1.2$ cm, $L = 53.5$ cm);
- b) SS2 - steady hydraulic gradient $i = 0.013$ ($\Delta h = 0.7$ cm, $L = 53.5$ cm); and
- c) SS3 - steady hydraulic gradient $i = 0.019$ ($\Delta h = 1.05$ cm, $L = 53.5$ cm)

The model was initially calibrated to case SS2 and then the model was performed for the above conditions.

Fig. 2 also shows the parameters extracted for model-data comparison these are namely: L_t , the total distance between the salt and fresh water source, L_s is distance of saltwater wedge toe from saltwater source, L_c is Distance of recharge canal from saltwater source, H_c is the peak of water table mound under the recharge canal, Δh is the head difference between fresh and salt water. No flow boundary conditions were imposed at the top and bottom of the computational domain.

The flow domain was discretized using spatially uniform quadratic elements. A mesh-independent solution was obtained with a mesh size of 0.5 cm. It should be noted that the SEAWAT is a saturated model, the aquifer was considered as a confined layer in this study, so the created head by recharge canal using the SEEP/W model as boundary condition was inserted into the SEAWAT model. The porous media used by Goswami and Clement (2007) was uniform silica beads of average diameter 1.1 mm with a hydraulic conductivity of 1050 m/day, the porosity of 0.385 and longitudinal and transverse dispersivities considered equal to 1 mm and 0.1 mm respectively. The relative density of seawater was 1.026 at the reference concentration of 1.0 at the seawater boundary.

2.4. Model skill

In order to have a precise simulation, it is necessary to calibrate the model. For comparing the measured data and simulated data statistical

indicators are used. The skill of the model prediction (P) relative to the observed data (O) was quantified using the following statistical indicators. The root-mean-square error (RMSE), the Correlation Coefficient (R^2) and the General Standard Deviation (GSD).

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (O_i - P_i)^2} \quad (4)$$

The square root of the correlation coefficient (R^2),

$$R^2 = \left[\frac{\sum_{i=1}^n (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^n (O_i - \bar{O})^2 \sum_{i=1}^n (P_i - \bar{P})^2}} \right]^2 \quad (5)$$

and the General Standard Deviation (GSD),

$$GSD = \frac{RMSE}{\bar{P}} \quad (6)$$

which in above equations O_i is the location of fresh-saltwater interface observed in the laboratory, P_i is the location of fresh-saltwater interface estimated using the model, \bar{O} is Average observed values and \bar{P} is Average modelled values.

The optimal value of RMSE and GSD are equal to zero, while the optimal square root of the correlation coefficient (R^2) is equal to 1 if a linear relationship holds.

2.5. Influence of the recharge canal on SWI

First, the numerical model SEAWAT was validated against the experimental data that its results are explained in section 3.1 and then in order to evaluate the effect of the proposed method on the control of saltwater intrusion, three scenarios were defined as follows:

- 1- Simulating the influence of location of recharge canal on the salt-water wedge

In this scenario, the influence of the position of the recharge canal on the extent of the saltwater intrusion was initially investigated using the constant head boundary conditions (SS1, see Fig. 2). After establishing a steady state (SS1), the water table mound under the recharge canal was computed using the SEEP/W and then applied as the upper boundary condition to the SEAWAT model to simulate the salinity distribution. The water table mound under the canal was held constant at 26.5 cm and the canal width was fixed at 2 cm. Several simulations were performed to determine the optimal location of the recharge canal in terms of the resulting position of the toe of the salt-water wedge. For this purpose, the water balance in the fresh water and saltwater tanks was considered constant and the position of the canal was considered

variable. Then, for different positions of the canal, the salt water wedge position was also calculated. The results of this scenario are discussed in section 3.2.

2- Determining the effect of hydraulic gradient changes on optimal location of recharge canal

In this section, the influence of the hydraulic gradient between the inland groundwater level and the saltwater level on the optimal location of the recharge canal is examined. To achieve the objective of this scenario, several hydraulic gradients were examined by changing the fresh water constant head level and then the optimal canal position was determined for each of the hydraulic gradients. In order to better understand, we calculated the repulsion ratio of saltwater using Eq. 7:

$$R = \frac{L_{S1} - L_{S2}}{L_{S1}} \times 100 \quad (7)$$

where R is repulsion ratio, L_{S1} is the initial toe position of the saltwater wedge and L_{S2} is the final toe position after the implementation of the recharge canal.

The results of this scenario are discussed in section 3.3.

3- Determining the effect of water table mound under the recharge canal on toe salt- wedge position

In order to determine how the water level changes in the canal influence the saltwater- wedge position, the SS1 case was selected. The recharge canal was placed in its optimal position that calculated in the first scenario from above and the hydraulic gradient was fixed at 0.022. Simulations for different water table mound profiles were then performed. The results of this scenario are discussed in section 3.4.

2.6. Case study

In order to better understand the influence of the surface water recharge canal, the model was subsequently applied to a field scale problem. Kahriz coastal aquifer in the vicinity of Lake Urmia in the northwest of Iran was simulated (Fig. 3) and Lake Urmia in north-western Iran is the largest inland lake in the country and one of the largest saline lakes in the world (Zarghami, 2011). The problem considered an unconfined aquifer system and the parameters used in the model are summarized in Table 1 (The parameters listed in Table 1 are estimated based on the characteristics of the area and field observations from the study area). The trapezoidal recharge canal (its dimensions is shown in Fig. 3) is located at a distance of 1000 m from the Lake coast. For simplicity, the water level of the lake and the aquifer water level were assumed to be constant at 1274 m (equivalent to the minimum ecological lake level) and at 1282 m (equivalent to the average head of last 15 years), respectively.

3. Results and discussion

3.1. Model calibration

Goswami and Clement (2007) have previously verified the performance of SEAWAT against their experimental data but did not publish their model skill indicators. Consequently, we performed our own calibration by varying the hydraulic conductivity, porosity and longitudinal and transverse dispersion for case SS2 (The model was calibrated based on experimental data of Goswami and Clement (2007) in SS2 mode). The best-fit values after the calibration of the model are summarized in Table 2. The simulations were carried out for the SS1 and SS3 modes based on the calibrated values of hydraulic conductivity, porosity and dispersion and then the calculated values and observed values were compared based on the statistical indices, the results of which are presented in Table 3. The results showed that the

SEAWAT model has high precision for simulation of the position of the saltwater wedge in SS1 with root mean square error (RMSE) equal to 1.03 cm (less than 10% of the average of measured data).

3.2. Influence of location of recharge canal on the saltwater wedge

Several simulations were performed to determine the optimal location of the recharge canal in terms of the resulting position of the toe of the salt-water wedge (i.e. where L_s/L_t is a minimum). The position of the toe of the salt-water wedge was expressed non-dimensionally as L_s/L_t (the lower the value of L_s/L_t , the greater the reduction of saltwater intrusion). The recharge canal location was expressed in non-dimensional form as L_c/L_t (L_c/L_t values of 0 and 1 correspond to a canal location at the saltwater source and freshwater source respectively). Fig. 4. shows the results of several simulations for different recharge canal distances from the saltwater source. The results showed that when the recharge canal is too close to the saltwater source and when the location of the recharge canal is farther from the saltwater source its effect on the control of saltwater intrusion is reduced thus there is an optimal location for the recharge canal, Fig. 4 indicates that the optimal canal location corresponds to $L_c/L_t \sim 0.19$ ($L_c = 10$ cm). A plot of the saltwater wedge position with and without the recharge canal is shown in Fig. 5. After the implementation of the recharge canal in its optimal location, the fresh-saltwater interface position retreated about 42% (6.64 cm). The saltwater receding after construction of the recharge canal is due to the increased pressure head created by the recharge water.

3.3. Influence of hydraulic gradient on the optimal location of recharge canal

The influence of the hydraulic gradient on the optimum canal location and the saltwater wedge position are shown in Figs. 6 and 7 respectively (L_o is the optimal distance of recharge canal from saltwater source, i.e. the minimum of L_s/L_t). The results indicate that the optimal canal location and saltwater wedge position are non-linearly related to the hydraulic gradient.

According to the results shown in Figs. 6 and 7, when the hydraulic gradient increases, the optimal location of recharge canal becomes nearer to the saltwater source and saltwater wedge recedes. From the results presented in Fig. 8, it can be seen that the optimal canal position depends on the toe position of the saltwater wedge before the construction of the canal (L_{S1}), and the relationship between them is linear. The repulsion ratio of saltwater wedge (R) in various gradients under the influence of the construction of recharge canal are presented in Table 4. The results indicate that construction of the recharge canal can result in receding saltwater-wedge between 37 and 45% depending on the hydraulic gradient. The difference between the toe salt- wedge position before the construction of the canal (L_{S1}) and the optimal position of the canal (L_o) in Table 4 shows that by increasing the hydraulic gradient, the optimum canal location becomes nearer the toe salt- wedge position. In general, the results show that more effective saltwater repulsion is achieved when the recharge canal is located in the portion near the toe of the saltwater wedge that this result agrees with the findings of research of Luyun Jr et al. (2011).

3.4. Influence of water table mound under the recharge canal on toe salt- wedge position

The influence of water table mound under the recharge canal on toe salt- wedge position is quantified in Figs. 9 and 10. The results show that the relationship between location of toe saltwater wedge position and peak of water table mound under the canal is an inverse linear relationship. That is, as the peak of water table mound under the canal increases, the saltwater wedge begins to recede. The saltwater wedge for different water table mound under the canal is depicted in Fig. 10,

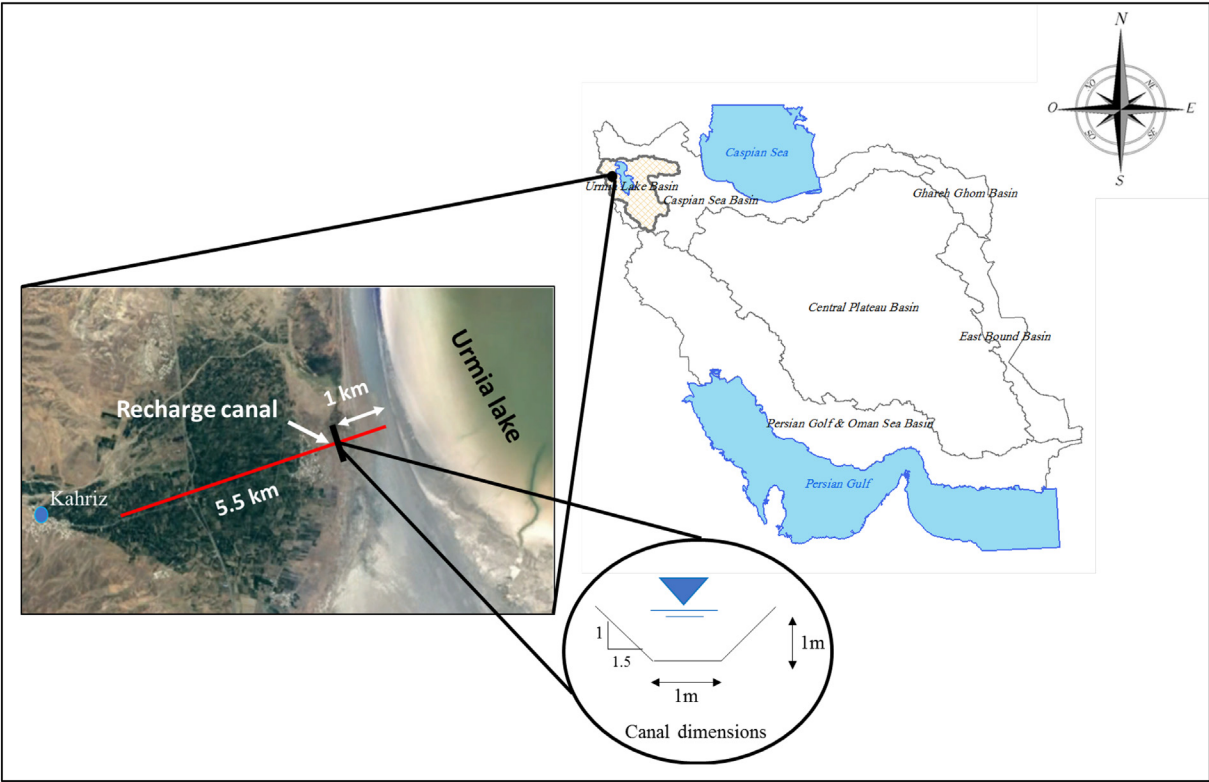


Fig. 3. Location of the Kahriz coastal aquifer in the northwest of Iran.

Table 1
The parameters used in the model.

Parameter	Value
Hydraulic conductivity	2 m/day
Porosity	0.3
Longitudinal and transverse dispersion	1 and 0.1 m
Specific yield	0.1
Density of saltwater	1150 kg/m ³
Length of the model	5525 m
Numerical grid size	$\Delta x = 25$ m and $\Delta z = 2$ m

Table 2
The best-fit values after the calibration of the model.

Parameter	Value
Hydraulic conductivity	1050 m/day
Porosity	0.385
Longitudinal and transverse dispersion	0.0005 and 0.00005 m

Table 3
Statistical indexes at SS1, SS2 and SS3 test.

Mode	Statistical indicators		
	RMSE [cm]	R ²	GSD
SS1	1.03	0.99	0.132
SS2 before calibration	0.67	0.99	0.06
SS2 after calibration	0.34	0.99	0.033
SS3	0.97	0.81	0.145

which clearly shows the effect of increasing water table mound under the canal on receding of saltwater wedge, so, in order to increase the water table mound should increase the recharge from the canal, which requires an increase in the dimensions of the canal.

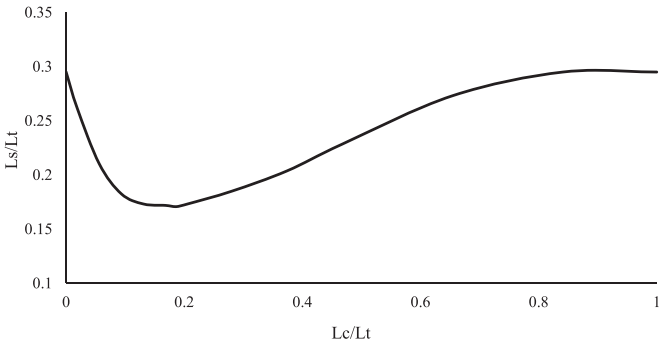


Fig. 4. The impact of constructing the recharge canal on saltwater intrusion and its optimal location.

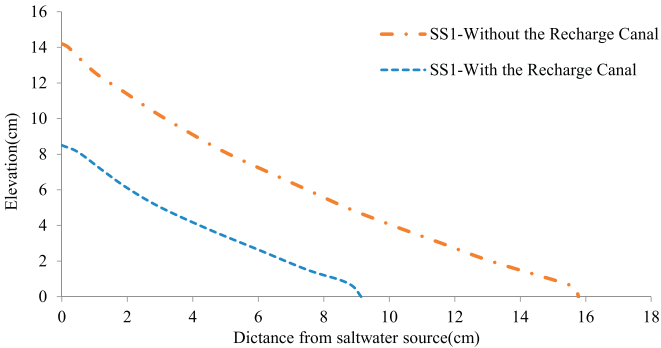


Fig. 5. Comparison of fresh-saltwater interface position with and without the recharge canal (the recharge canal is located in its optimal location).

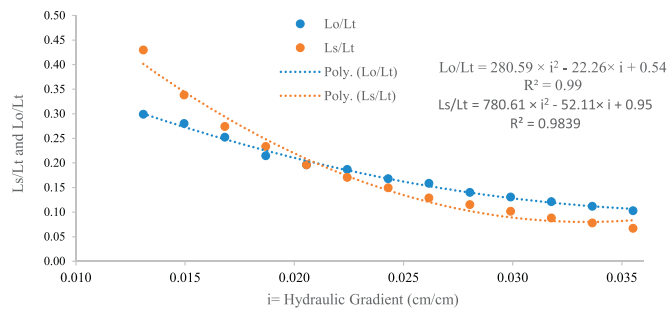


Fig. 6. Relation of parameters Lo/Lt and Ls/Lt vs hydraulic gradient.

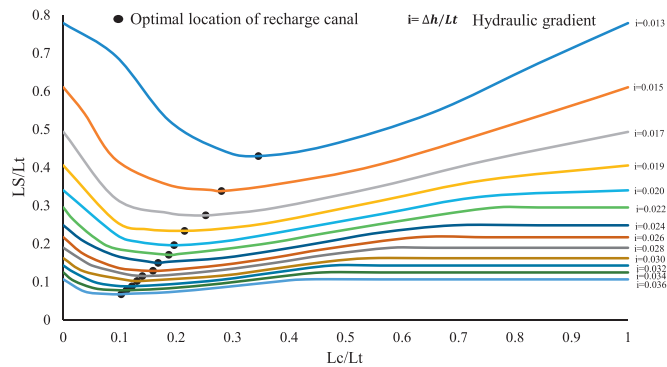


Fig. 7. The optimal location of recharge canal for different hydraulic gradients.

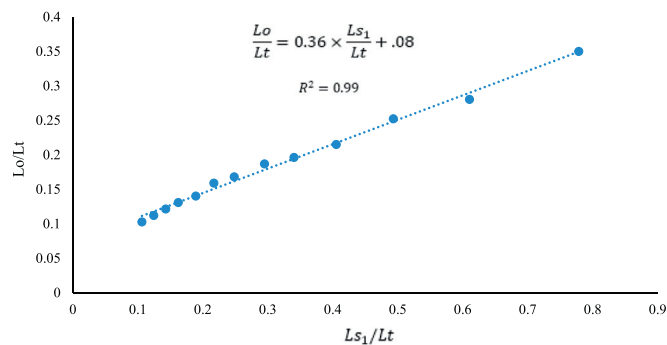


Fig. 8. Relation of parameter Lo/Lt and Ls/Lt .

Table 4

The repulsion ratio of the saltwater wedge (R) in various gradients under the influence of the construction of recharge canal.

i (hydraulic gradient) (cm/cm)	Ls_1 (cm)	Ls_2 (cm)	$Ls_1 - Lo$ (cm)	R (%)
0.013	41.7	23.0	23.15	45
0.015	32.7	18.1	17.66	45
0.017	26.4	14.7	12.88	44
0.019	21.7	12.5	10.18	42
0.02	18.2	10.5	7.70	42
0.022	15.8	9.1	5.78	42
0.024	13.3	7.9	4.29	41
0.026	11.6	6.9	3.11	41
0.028	10.1	6.2	2.62	39
0.03	8.68	5.4	1.68	38
0.032	7.65	4.7	1.15	38
0.034	6.66	4.2	0.66	37
0.036	5.69	3.6	0.19	37

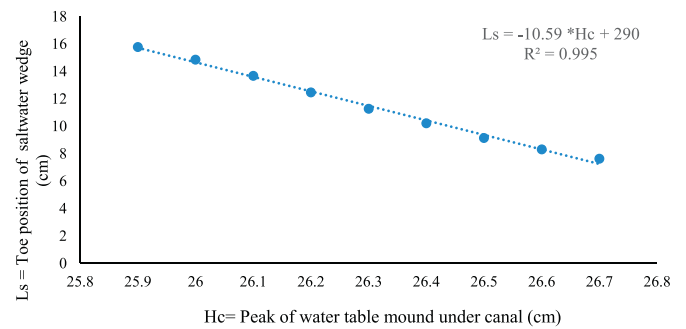


Fig. 9. Relation of toe position of saltwater wedge and water level in the canal location.

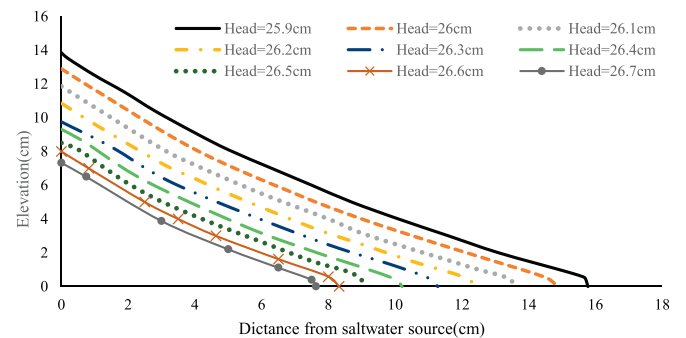


Fig. 10. Saltwater wedge position for different water table mound under the canal.

3.5. Results of case study

To simulate the effect of the recharge canal on saltwater intrusion at the field scale, Kahriz aquifer was simulated under the conditions outlined previously in Section 2.6. After the establishment of steady-state conditions without a recharge canal, the saltwater wedge was located at a distance of 1370 m from the lake (Fig. 13). Then based on the relationships presented in Figs. 6 and 8 and properties of Kahriz aquifer ($Lt = 5525$ m, $Ls_1 = 1370$ m, $i = 0.0014$) two values for the optimal canal location were calculated at 2762 and 1000 m from saltwater source, respectively. Then using the SEEP/W model, the water table mound under the recharge canal was calculated (Groundwater level increased by 10 m in the canal site). As you can see in Fig. 11, the results of the SEEP/W model showed that after 8 months from the construction of the canal, the groundwater level reached the water level of the canal.

The Saltwater wedge position before and after the construction of the recharge canal after establishing steady-state conditions for both canal positions is shown in Fig. 12. The results show that the presence

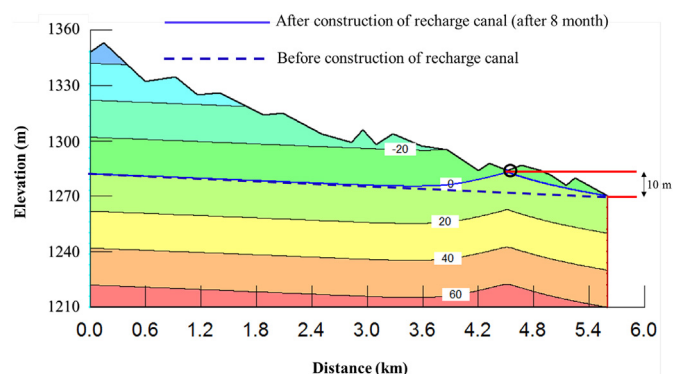


Fig. 11. Water table before and after construction recharge canal.

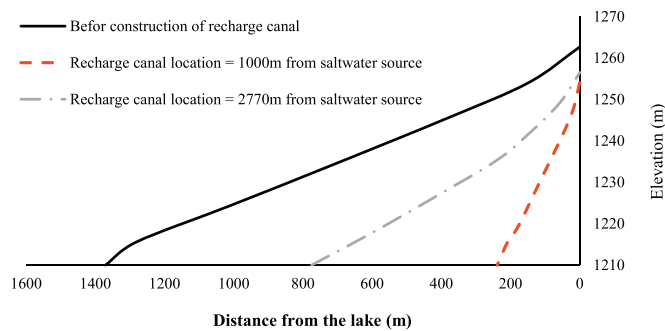


Fig. 12. Comparison of Saltwater wedge position before and after construction recharge canal for $L_c = 1000$ m and $L_c = 2770$ m.

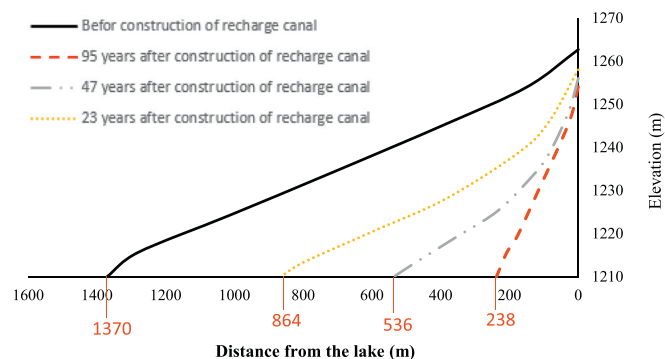


Fig. 13. The Saltwater wedge position during the saltwater wedge receding ($L_c = 1000$).

of a recharge canal initially prevents the advancement of the saltwater wedge and then led to recession of the saltwater wedge. According to the results, the position of the canal at a distance of 1000 m from the lake can be more effective than its position at a distance of 2770 m. Therefore, calculating the canal position based on the relationship presented in Fig. 8 gives a better result.

Fig. 13 shows the saltwater wedge position for the canal created at a distance of 1000 m from the lake in different times after the construction of the canal. After rising groundwater level under the canal, saltwater wedge begins to recede, after 95 years the steady-state conditions occurred and saltwater wedge situation became stable and the saltwater wedge is located at 238 m from the lake, the results of this section clearly show that a recharge canal with relatively small dimensions could have a significant effect on reduction in the extent of the saltwater intrusion.

4. Conclusions

In this research, an alternative method for reducing the extent of saltwater intrusion by implementing a surface freshwater recharge canal has been examined. A numerical model (combining SEAWAT and SEEP/W) has been developed and calibrated against the experimental data of Goswami and Clement (2007). The results indicate that the implementation of a surface water recharge canal is effective in reducing the extent of saltwater intrusion. Under a constant hydraulic gradient, when the recharge canal is either too close or too far from the saltwater source, its effect on the control of saltwater intrusion is reduced.

This research showed that when the hydraulic gradient increases, the optimum location of the recharge canal approaches the location of the saltwater source. The optimal canal position depends on the toe position of the saltwater wedge, and the relationship between them is almost linear and more effective saltwater repulsion is achieved when the recharge canal is located in the portion near the toe of the saltwater

wedge. The recharge canal can result in a recession of the saltwater wedge between 37 and 45% depending on the hydraulic gradient.

Increasing the water level in the canal increases the elevation of the water table mound under the canal, leading to an increased reduction in the extent of the saltwater intrusion. Consequently, having the ability to control the water level in the recharge canal will provide a greater level of control on saltwater intrusion. It should be noted that the dimensions of the canal depending on the texture of the soil, the rate of inlet water from the river and the required water recharge rate for making an appropriate water table mound under the canal. The results of the case study showed that a recharge canal with relatively small dimensions could have a significant effect on reduction in the extent of the saltwater intrusion. Creating this canal can also provide a beautiful landscape around the lake.

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