

## ORIGINAL RESEARCH PAPER

# Laboratory investigation of water extraction effects on saltwater wedge displacement

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Received 20 September 2016; revised 11 November 2016; accepted 28 November 2016; available online 1 December 2016

**ABSTRACT:** There is a close connection between saltwater intrusion into aquifers and groundwater extraction. Freshwater extraction in coastal aquifers is one of the most important reasons for the saltwater intrusion into these aquifers. Condition of extraction system such as well depth, discharge rate, saltwater concentration and etc. could affect this process widely. Thus, investigating different extraction conditions comprises many management advantages. In the present study, the effects of freshwater extraction on saltwater interface displacement have been investigated in a laboratory box. Three different well depths (H) were considered with combinations of 3 different extraction rates (Q) and 3 saltwater concentrations (C) for detailed investigation of the effects of these factors variations on saltwater displacement. SEAWAT model has been used to simulate all the scenarios to numerically study of the process. The experimental and numerical results showed that when the C and Q rates were small and the well depth was shallow, the saltwater interface wouldn't reach the extraction well, so the extracted water remained uncontaminated. When the C and Q rates were increased and the well was deepened, the salinity of the extracted water became higher. When the Q and C rates were high enough, in the shallow well depth, the final concentration of the extracted water was low but a huge part of the porous media was contaminated by the saltwater, furthermore when the well was deepened enough, the final concentration of the extracted water was increased but a small part of the porous media was contaminated by the saltwater. Finally, the results showed that when the Q and H rates were high enough, the extraction well behaved like a barrier and didn't allow the advancing saltwater wedge toe to be intruded beyond the wells.

**KEYWORDS:** Extraction rate; Interface; Laboratory box; Saltwater concentration; SEAWAT; Well depth

## INTRODUCTION

The needs for freshwater in coastal areas and islands are rapidly increasing due to population growth and tourism. In these areas, groundwater is generally the most important freshwater resource which is threatened by seawater intrusion (Ketabchi *et al.*, 2016). Increasing of freshwater demand in coastal areas has increased the number of extraction wells. One of the goals of coastal aquifer management is to maximize freshwater extraction without causing

the invasion of saltwater into the wells (Cheng *et al.*, 2000; Shitu *et al.*, 2015). Water withdrawal from coastal aquifers can cause the vertical rise of saltwater and a reduction of the freshwater zone below pumping wells, a process called up-coning. The rate and extent of saltwater up-coning depend on a number of factors, including hydraulic properties of aquifer systems, pumping rate and duration, initial position of the interface, density contrast between freshwater and saltwater, and other factors such as dispersion and sorption effects, groundwater recharge, regional flow rate, and the well and aquifer geometries (Werner *et al.*, 2013). Pumping or extraction effects on saltwater

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Note: Discussion period for this manuscript open until March 1, 2017 on GJESM website at the "Show Article".

intrusion in an aquifer can be investigated through field scale studies, laboratory scale studies, numerical methods and optimization methods. Field scale studies mainly focused on optimizing the groundwater pumping. Optimization methods are applied to address various practical questions relating to pumping operation, well placement, design of artificial recharge schemes and other mitigation measures, trade-offs between environmental and socioeconomic factors, and interdependencies between surface and subsurface systems (Werner *et al.*, 2013). In the past literature, many optimization methods have been reported by the researchers as Elitist Continuous Ant Colony Optimization (ECACO) algorithm (Ataie-Ashtiani and Ketabchi, 2011), genetic algorithm (Cheng *et al.*, 2000; Park and Aral, 2004; Mantoglou and Papantoniou, 2008; Ketabchi and Ataie-Ashtiani, 2015), nonlinear optimization problem which is solved using Sequential Quadratic Programming (SQP) (Mantoglou, 2003), dynamic programming (Duarte *et al.*, 2015), simulation-optimization modeling approach (Singh, 2014; Gorelick and Zheng, 2015). Laboratory scale studies have been increased in recent years. Researchers investigated the SI process in many aspects using an experimental and controlled box (Chang and Clement, 2013; Goswami and Clement, 2007; Luyun *et al.*, 2009; Morgan *et al.*, 2013; Abdollahi-Nasab *et al.*, 2010; Zhang *et al.*, 2001). Studying through these boxes has many advantages such as: controlling different conditions, implementing many scenarios, significantly decreasing the process time and so on. Laboratory scale methods have mostly studied the dynamics of the saltwater interface, dispersivity factors, controlling of saltwater intrusion through barriers and up-

coning phenomenon. Researchers also have demonstrated that the laboratory scale methods are a reliable approach to investigate the SI processes and a good benchmark for analytical and numerical solutions. Numerical and simulation methods have become irreplaceable tools to gain insight in real world SI processes. Most numerical codes solve a coupled system of variable density flow and solute transport equations. One of the most widely used codes is SEAWAT (Langevin *et al.*, 2008). This model specifically has been designed for the simulation of SI. Goswami and Clement (2007), Chang Clement (2012), Luyun *et al.* (2009), Rasmussen *et al.* (2013), Green *et al.* (2014) and many other researchers have showed the applicability of SEAWAT in their studies. Many factors can affect the freshwater extraction such as extraction rate, well geometry (e.g. depth, diameter and etc.), concentration difference between salt and fresh waters. Studying the effect of these factors could be an important management concern. To the best of our knowledge, this is the first time that water extraction effects on saltwater intrusion are being investigated altogether using a laboratory box. In a field scale, it is impossible to change the factors to study their effects on saltwater intrusion, so the laboratory method is an excellent way to study the phenomena.

This study has been carried out in the Laboratory of Irrigation and Drainage in Faculty of Agriculture, University of Tabriz in 2016.

## MATERIAL AND METHODS

### Experimental method

Fig. 1 shows the experimental box used in this study. The box was constructed using steel plates at

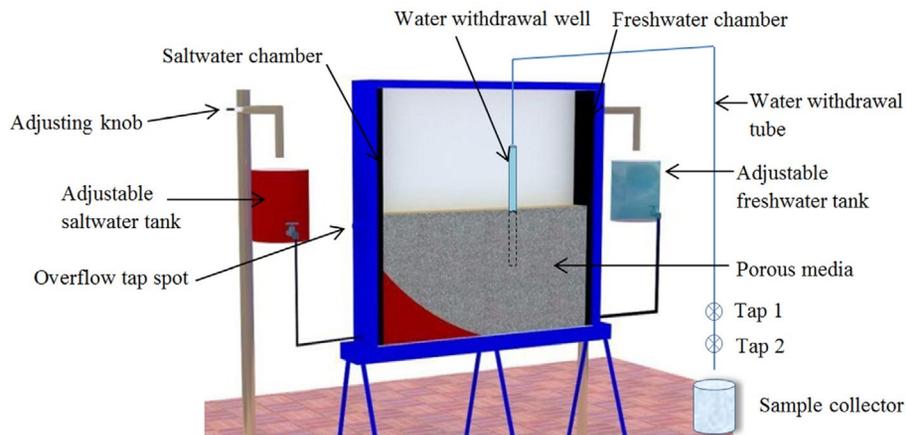


Fig. 1: Details of the experimental box used in this study

back, right and left sides and a Plexiglas plate at the front side. There were two chambers at the left and right sides of the box as the reservoirs of the saltwater and freshwater, respectively. Also a chamber was placed between the mentioned side chambers in the central part of the box that was filled with silica sand up to the height of 50 cm. The average diameter of the sand grains was 1 mm. The internal dimensions of the central chamber were 110cm×100cm×5cm (length\*height\*thickness) and both the side chambers had 5cm length and were separated from the porous sand medium chamber by two fine mesh sheets. This narrow tank was used to simulate the two-dimensional flow of an unconfined aquifer. The water heads in the side chambers were controlled by the two adjustable tanks that were connected to them. A well was set by inserting a metal tube to penetrate the porous medium into the determined depth. About 3 cm of the bottom part of the tube was reticulated to allow water to infiltrate into the well. A narrow plastic tube was placed into the well to extract the water. As shown in Fig. 1, the water was extracted from the well using the siphon method by keeping the level of exit tap lower than the well bottom. Saltwater was prepared by dissolving commercial salt in tap water in a large tank. Furthermore, a tap spot was set at the top of saltwater chamber to discharge the overflow coming from the freshwater chamber. The salinities of the fresh and salt water were measured using a laboratory bench-top meter. This saltwater was colored by a red food dye to distinguish it from the freshwater. Some researchers have used food dye in their laboratory scale experiments successfully (e.g. food color (Kalejaiye and Cardoso, 2005), potassium permanganate/ fluorescein (Oostrom *et al.*, 1992) and Rhodamine WT (Schincariol and Schwartz, 1990; Simmons *et al.*, 2002), food dye (Goswami and Clement, 2007; Chang and Clement, 2012; Chang and Clement, 2013), food color, New Coccine Acid Red 18 (C.I. Number 16255) (Luyun *et al.*, 2009)). In this study, about 5 g dye was added to 10 liters of saltwater. A digital camera (Canon PowerShot SX520 HS) was used to take pictures during the experiments. The hydraulic conductivity (K) of the replaced sand in the tank was measured using the in-situ method described in Simmons *et al.* (2002) and Darcy law. The average value of the estimated conductivity was 1 cm/s. For determining the dispersivity coefficients, the methods in the

literatures were used. Some researchers have used the average grain diameter as the longitudinal dispersivity value and assumed the transverse dispersivity value to be about 1/10 of the longitudinal dispersivity amount (Oswald and Kinzelbach, 2004; Goswami and Clement, 2007; Johannsen *et al.*, 2002; Luyun *et al.*, 2009; Konz *et al.*, 2009). Some others have used the calibration method to determine these coefficients (Abarca and Clement, 2009; Chang and Clement, 2013). In the present study, the value of longitudinal dispersivity was firstly assumed to be 1 mm, equal to the average diameter of the grains with a transverse dispersivity value of 0.01 mm. These coefficients were also determined by calibrating the numerical results with the experiments. The results of these two methods had a good correspondence, so the assumed values of the dispersivity coefficients were accepted. The average porosity of the porous medium was measured by both the volumetric and gravitational methods and its value was 0.38. Table 1 shows all the experimental parameters used in this study.

#### Experimental procedure

The porous medium tank was packed under saturated conditions in layers of 5 cm to avoid air entrapment. The porous medium and chambers were initially filled with tap water from the overhead freshwater tanks. A constant gradient head was created so that a freshwater flow from right to the left was established. For creating this gradient, the freshwater and saltwater chamber heads was determined as 49 cm and 48 cm respectively. Extraction rate was adjusted according to the experiment using tap 2 on well tube. After adjusting the desired rate, tap 1 on well tube was closed. Saltwater intrusion started by opening the saltwater tank tap and allowing it to enter to the left chamber. Saltwater wedge started to invade from the left chamber toward the porous media until

Table 1: Experimental parameters

parameter	value
Porous media dimensions	50cm × 110cm × 5 cm
Hydraulic conductivity	1 cm/s
Porosity	0.38
Saltwater concentrations	25, 36, 50 g/L
Freshwater concentration	10 g/L
extraction rates	0.05, 0.12, 0.25 L/min
Well depths (from sand surface)	0.12, 0.25, 0.36 m
Longitudinal dispersivity	0.001 m
Transverse dispersivity	0.0001 m

it reached the steady state condition. The movement of the wedge was recorded by the camera every 2 minutes. The location of the wedge in steady state condition depended on the saltwater concentration. After establishing the steady state condition, water withdrawal through the well was started by opening the tap 1. Concentration of the extracted water was measured every 2 minutes. The system was allowed to reach the final steady state condition. The effects of water withdrawal on the interface were investigated using the measured concentrations and photos. This experiment process was repeated for 3 different well depths, 3 different extraction rates and 3 different saltwater concentrations to study the effect of these parameters to the interface movement.

## RESULTS AND DISCUSSION

The different scenarios were distinguished by symbols, hence, for different concentrations, the notations of C1, C2 and C3 were used. Similarly, for well depths and extraction rates, the same procedure was considered (i.e. H1, H2 and H3 for well depths and Q1, Q2 and Q3 for the extraction rates). For example, H1Q2C3 means that the scenario refers to H1 well depth, Q2 extraction rate and C3 concentration. First, one of the scenarios from beginning to the end is shown here by photos and simulation data to figure out and illustrate the whole process of invasion and up-coning processes. Fig. 2 shows the C2H2Q2 scenario results in both laboratory and numerical methods. As shown in the Fig. 2, the saltwater wedge started to invade toward the porous medium. Saltwater moved beneath the freshwater due to the density difference. But where the fresh and salt waters reached to each other, an

interface was created due to the conflict of the two waters. The concentration of the salt varies only through this interface. The width of the interface in a laboratory system is very small comparison to a field scale. Goswami and Clement (2007) has reported the interface zone as 1cm. Abarca and Clement (2009) also measured the thickness of the interface as about 1.5 cm and Luyun *et al.* (2009) determined the interface zone as about 1 cm in their laboratory scale systems. The saltwater intrusion continued until it reached the steady state condition. After the water extraction started, the interface started to move up; this process is called up-coning. The location of well bottom (that extraction occurred) was signed by a dark point on the front glass. Up-coning caused the extracted water quality to get worse over the time. In addition, water extraction caused the saltwater wedge to move further compared with no-extraction condition. Fig. 3 shows the extracted water salinity (breakthrough curve) after the start of the extraction in both the experimental and numerical models in C2H2Q2. As shown in relevant picture in Fig. 3, after a short time, the saltwater reached the well and normally an increase in salinity of the extracted water was expected. According to the results at this stage, the salinity of the extracted water had an increasing trend which approximated to a constant value by passing the time. This constant value depended on various parameters such as saltwater concentration, extraction rate and well depth. These explained processes dominated the whole scenarios and the influence of relevant parameters on this phenomenon were investigated and assessed. Similar photos were obtained for other experiments but are not shown for brevity. It should be noted that the simulated

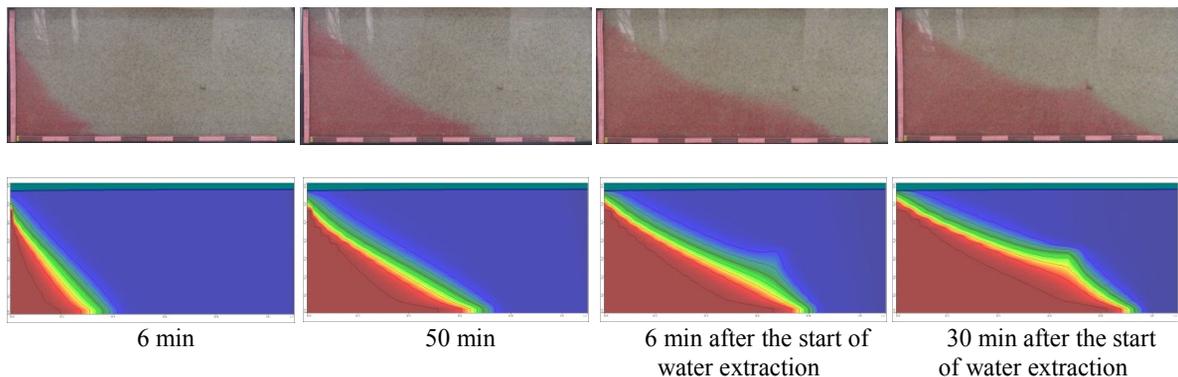


Fig. 2: Illustration of the whole process of saltwater invasion from beginning to the end in H2C2Q2 experiment

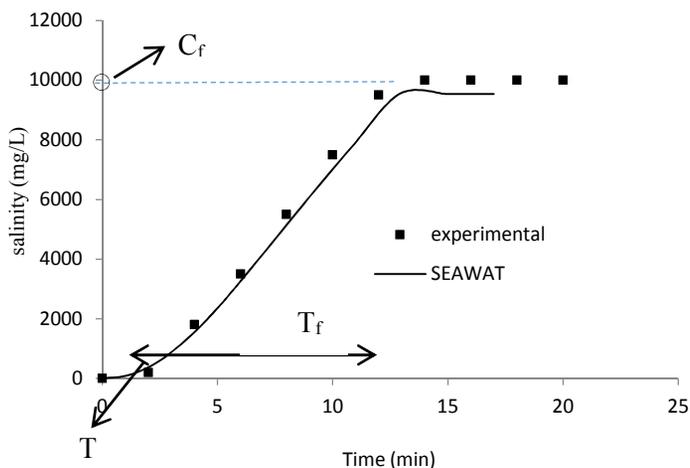


Fig. 3: Breakthrough curve obtained from H2C2Q2 experiment

results by SEAWAT were corresponded well with the experimental results however SEAWAT slightly overestimated the salinity of the extracting water.

Dispersion effect can be easily seen in simulation pictures whereas the interface appeared to be sharp in the laboratory experiments at the same times, albeit experimental results rely on visual inspection of photographs.

*Saltwater concentration effect*

As previously mentioned, three different saltwater concentrations were used in the experiments (25, 36 and 50 g/L). Analysis of the obtained intrusion photos showed that the increasing the concentration made the saltwater wedge move a further distance and the top point of the saltwater wedge at the inlet chamber move slightly downward. Generally, it can be concluded that the interface moved down and forward by increasing the concentration of

saltwater. But the shape of the saltwater in the final steady state condition around the extraction point did not vary significantly by changing the saltwater concentration. Thus, the concentration effect was not analyzed properly and the extracted water concentration was analyzed over the time to assess the effect of the saltwater concentration on the extracted water quality. In overall, the breakthrough curve of the extracted water from the well had a shape like the one that illustrated in Fig. 3. If the Fig. 3 is broken down into some parts for better understanding the conception, 3 important characteristics are distinguished to be analyzed; First, the time needed to the saltwater to reach the well (or the time that the concentration rise was observed,  $T_i$ ), second, the time needed to the extracted water to reach a constant concentration value (the time that the chart started to be horizontal,  $T_p$ ) and third, the extracted water finalized concentration ( $C_p$ ). These 3 characteristics

Table 2: The values of  $T_i$  and  $T_p$  in all the experiments (min)

	Q1			Q2			Q3		
	C1	C2	C3	C1	C2	C3	C1	C2	C3
H1	*, *	*, *	2.5, 27	*, *	7, 18.5	1, 52	9.5, 21.5	2.5, 16.9	0, 55
H2	*, *	2, 11.1	0, 7.75	4, 9	1.9, 12.9	0, 10	5, 15.7	1.5, 12.5	0, 10.7
H3	*, *	0, 8.3	0, 5	5.7, 11.9	0, 7.8	0, 2.5	2.5, 10.5	0, 7.5	0, 3.6

Table 3: Final constant concentration ( $C_p$ ) in all the experiments (mg/L)

	Q1			Q2			Q3		
	C1	C2	C3	C1	C2	C3	C1	C2	C3
H1	0	0	6050	0	2340	13300	2753	6784	18420
H2	0	3697	15500	1006	9540	23000	5056	12440	26420
H3	0	15850	40800	3303	14790	33950	5960	13790	30170

are shown in Fig. 3. Due to the excessive number of experiments and charts, these characteristics have been used in Tables 2 and 3 in order to facilitate the data analysis. For better comparison and analysis of the different factors effect on the values of  $T_i$  and  $T_f$ , the Table 2 has been prepared. The final constant concentrations and relative concentrations are presented in Tables 3 and 4 respectively. The relative concentrations were calculated as a ratio between the final constant concentration and the maximum possible concentration in each experiment (the maximum possible concentration in C1, C2 and C3 experiments were 25000, 36000 and 50000 mg/L respectively).

As shown in Table 2,  $T_i$  decreased in all the experiments by increasing the saltwater concentration. In some scenarios, the saltwater didn't reach the well and no record registered for these scenarios (marked as "\*" in Table 2). This is due to the lower saltwater concentration and extraction rate. In some cases, the saltwater immediately reached the well and no time needed for the process (showed as "0"). According to the results when the saltwater concentration increased, significant advancement of saltwater towards the well is observed. This caused the saltwater to reach the well sooner and make the  $T_i$  small. Comparison of the  $T_f$  values shows that the  $T_f$  had erratic behavior against the concentration changes. But in H3,  $T_f$  obviously decreased by concentration. In other words, when the well was close to the saltwater wedge and the saltwater concentration increased, then the extracted water concentration reached the constant value in a shorter time.

As Table 3 indicates, the final constant concentration value ( $C_f$ ) obviously increased by increasing the

saltwater concentration. In Table 4, the relative concentration ratio clearly increased by increasing C value. It means that, in the same H and Q conditions, the final constant concentration reached a high relative amount as the C value increased.

One of the visual characteristics of the fresh-salt water interface is the toe position ( $X_{toe}$ ), namely the distance of the saltwater wedge toe from the coordinate origin ( $X=0$ ). The toe position information have been gathered in the final steady state condition in all the experiments in Table 5. According to the recorded values in Table 5, the toe significantly moved further when the saltwater concentration increased. In other words, when the concentration of the saltwater increased, the effect of density driven flow became remarkable and caused further intrusion of the wedge into the porous media.

*Water extraction rate effect*

As mentioned before, the 3 different extraction rates were used to investigate the effects of this factor on the movement of the interface. Prior to the experiments, these rates were selected through some trial and error tests in both the numerical and physical models.

According to Table 2, in Q1C1 experiments at all the depths, the saltwater has not reached the well. But, in the all Q3 experiments, the saltwater has reached the well. When Q was increased, the saltwater wedge was reached the well sooner. Analysis of the  $T_f$  values in Table 2 showed that when the Q increased, the extracted water salinity reached a constant value in a longer time. As it is evident from Tables 3 and 4, the final constant concentration and the final relative constant concentration were

Table 4: Final relative concentration in all the experiments

	Q1			Q2			Q3		
	C1	C2	C3	C1	C2	C3	C1	C2	C3
H1	0.00	0.00	0.12	0.00	0.07	0.27	0.11	0.19	0.37
H2	0.00	0.10	0.31	0.04	0.27	0.46	0.20	0.35	0.53
H3	0.00	0.44	0.82	0.13	0.41	0.68	0.24	0.38	0.60

Table 5: Toe position ( $X_{toe}$ ) (cm) in the final steady state condition in all the experiments

	Q1			Q2			Q3		
	C1	C2	C3	C1	C2	C3	C1	C2	C3
H1	52	93	109	68	98	109	78	97	109
H2	52	89	110	66	92	109	77	85	102
H3	59	81	104	70	79	96	71	76	85

increased when there was an increase on the extraction rates. Relative concentrations in Table 4 demonstrated that when the freshwater exploitation from the aquifer increased, the saltwater moved toward the well with more intensity, subsequently, the final concentration of extracted water became higher and higher. This result implies that the extraction rate had a tremendous effect on saltwater intrusion management in coastal aquifers. Unlike concentration, extraction rate had significant effects on the final shape of the interface at the final steady state condition. Fig. 4 compares the final situation of the interface in three different extraction rates in H2C2 experiments. When the extraction rate increased, the saltwater wedge moved to further distance and the up-coning process was intensified. Fig. 4 also illustrates the velocity vectors along with salinity contours simulated by SEAWAT model. In Q1 experiment, the scale factor of vectors has been increased to better visualization of the vector directions. As shown in these pictures, in Q1 experiment, the lower extraction rate caused that a large part of the freshwater overflow out through the top of the saltwater chamber. When the extraction rate is increased (Q2, Q3), the greater part of fresh and salt water moved towards the well and the overflow amount significantly decreased. It can be concluded that in no water withdrawal, the saltwater moved from the left chamber toward the wedge and conflicted with freshwater and then moved upward in parallel with the wedge and overflow out along with freshwater through the top of the left chamber. But when the water extraction was applied, a part

of fresh and saltwater moved toward the well and this caused the saltwater wedge to advance deeply into the aquifer and contaminate the extracted water. When the extraction rate was increased, a greater part of the salt and fresh water moved toward the well and caused the wedge to move further and made the quality of extracted water be worse than before. Another point is that in a greater extraction rate, a greater part of freshwater moved toward the porous media and this caused the toe of the wedge to move a little backward. In addition, this increment of the extraction rate made the top of saltwater wedge (near the surface) move forward while no freshwater overflow through the top of the saltwater chamber. This result can be seen in Fig. 4 comparing the Q2 and Q3 pictures. The recorded values in Table 5 indicate that in H1, when the Q amount was increased, the toe was intruded more distance. In H2C1 and H3C1 the toe position had the same trend, but in H2 (C2, C3) and H3 (C2, C3) when the Q amount was increased, the toe was moved backward.

#### Well depth effect

It is clear that when the depth of the well decreases, the extracted water is less affected by the saltwater interface. This can be seen through the recorded values in Table 2. In H3 experiments (especially in C2 and C3), the saltwater wedge immediately reached the well. In deeper well depth conditions, the salinity of extracted water reached the constant concentration in longer periods. In other words, when the wedge toe and the well depth were

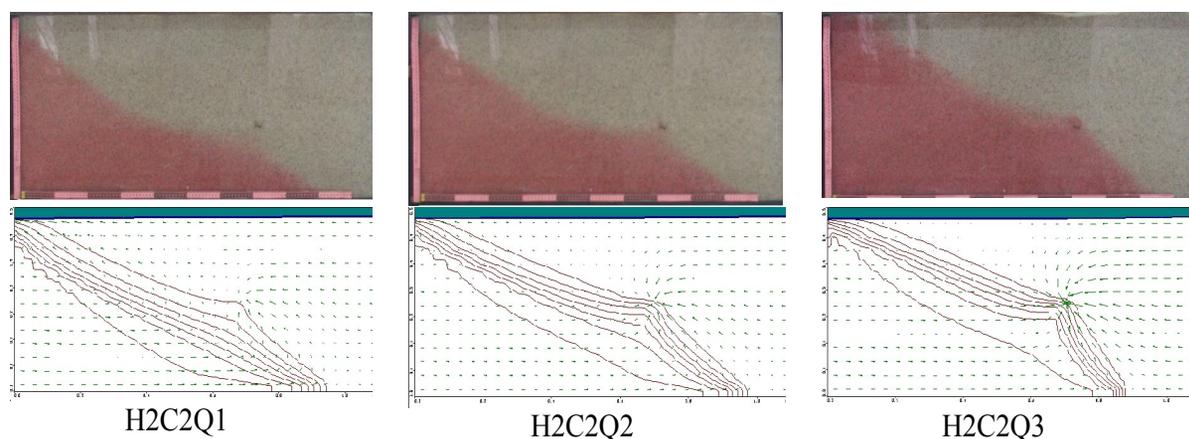


Fig. 4: Final steady state condition in three different extraction rates in H2C2 experiments

close to each other, the  $T_i$  and  $T_f$  significantly were decreased. The values in Tables 3 and 4 demonstrate that the final constant concentration and relative concentration of the extracted water were increased by deepening the well depth.

Fig. 5 shows the final shape of the saltwater interface in second (final) steady state condition in 3 different well depths in C3Q3 experiments. As shown in the photos, the well depth has a great effect on the final shape of the wedge. In a shallow well depth (H1), the final salinity of the extracted water decreased, however the wedge moved much further and the saltwater contaminated a huge part of the porous media (If the extraction rate was high enough). But in deep well depth (H3), the saltwater wedge reached the well very soon and the final salinity of the extracted water highly increased, although, the saltwater contaminated

a small part of the porous media. Hence, it can be concluded that when the well penetrated deeply into the aquifer, it operated like a barrier and didn't allow advancement of the saltwater wedge front beyond the wells, but the salinity of the extracted water from the well increased. Fig. 5 also shows the velocity vectors obtained from SEAWAT model. The photos show that in H3 experiment, a part of pervaded freshwater from the right chamber moved up and overflow out through the top of saltwater chamber. In addition, almost no part of the saltwater moved out through the overflow. Hence, the final salinity of the extracted water in this case was high in a deeper well depth.

Combined effects

Fig. 6 illustrates the final concentration and final relative concentration in all the experiments for

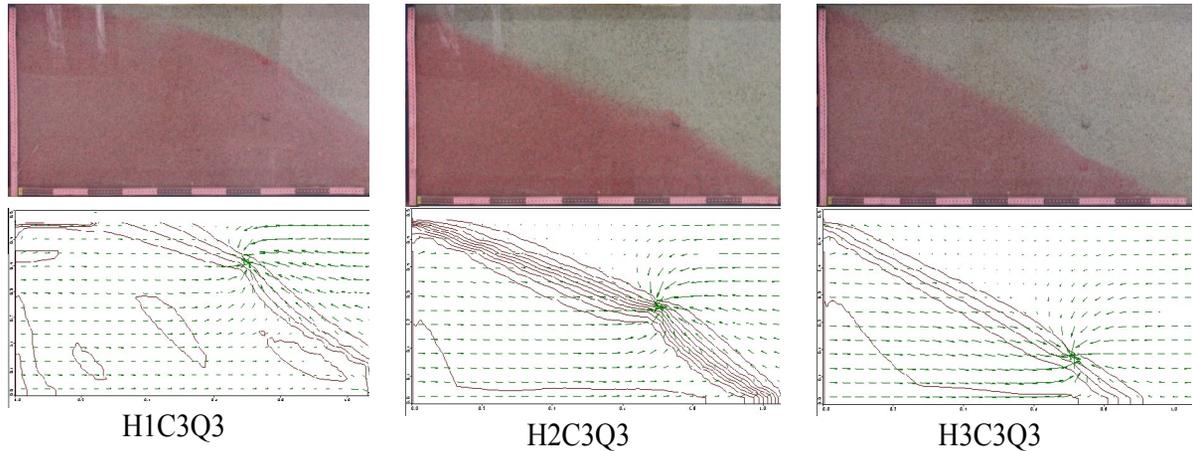


Fig. 5: Final steady state condition in three different well depths in C3Q3 experiments

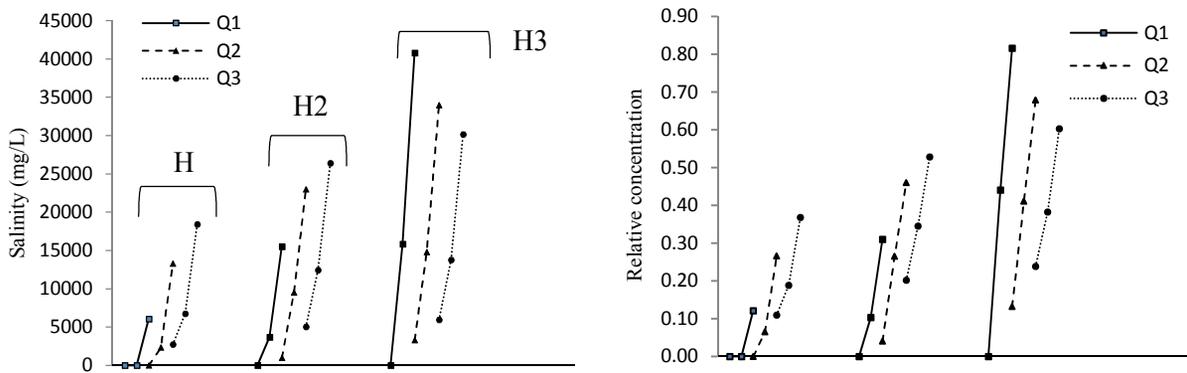


Fig. 6: Comparing the combined effects of the factors on the final salinity of the extracted water (each group of lines indicate the H, the line type indicates the Q and the points on every line indicate the Cs)

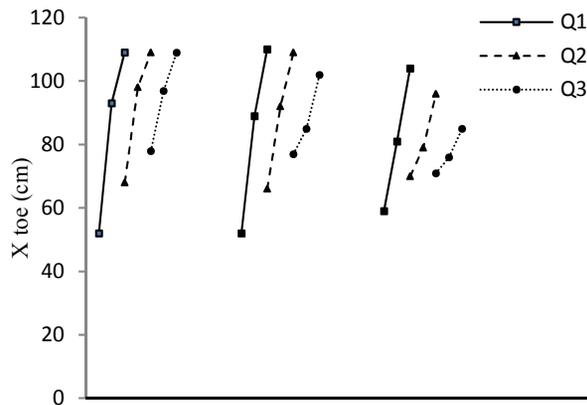


Fig. 7: Comparing the combined effects of the factors on the toe position at final steady state condition

better comparison and analysis of the differences between all the scenarios. In Fig. 6, every group of lines indicates a defined H, each type of the lines (continuous, dashed, dotted) indicates a defined Q and the three points on every line indicate C1, C2 and C3 respectively.

As shown in Fig. 6, in H1 and H2 well depths, when the Q and C amounts were increased, the final concentration reached a higher value, so Q and C had an interaction effect on each other. But in H3 (when the well was deepened near the toe), there were two different behaviors. In C1 concentration, the same interaction effect was observed. But, in C2 and C3, Q had an opposite effect on C so the final concentrations in Q2 and Q3 in the same Cs were decreased. It can be concluded that when the well was deepened enough, increasing the extraction rate lead to extraction of more freshwater from the right chamber, hence the final concentration of the extracted water was decreased.

If the Q rate is assumed to be constant, it will be possible to analyze the combined effect of H and C. For this purpose, consider one type of the lines (for example, continuous lines). As evident in Fig. 6, H and C had an interaction effect to each other in all the experiments. The rate of this effect decreased as

the well depth deepened (the differences between H1 and H2 are more than that between H2 and H3).

When the well depth was increased, this created a high risk of advancement of the interface toward the well with increase of the extraction rate.

The present study also illustrates the toe position in the final steady state condition in all the experiments. Fig. 7 shows that deepening the H significantly diminished the C effect on the toe position. As seen in Fig. 7, when H was increased, the lengths of the lines were shortened. This indicates that in a deeper H conditions, changing the C had a minor effect on the toe position. Also, H had the same effect on Q, so that in a deeper H, changing the line length among the three types of the lines were decreased. Besides, when H and C were increased, Q had an opposite effect on the toe position. As shown in Fig. 7, in H3, when the Q was increased, the toe was moved backward.

*Quantifying the results*

In previous sections, the effects of some factors on saltwater intrusion were investigated using photos and charts. In this section, these effects were analyzed by quantifying the results.

In first steady state condition (no extraction), the

Table 6: Increment percentage of the toe intrusion versus the increment percentage of saltwater concentration

	Q1		Q2		Q3	
	C1→C2	C2→C3	C1→C2	C2→C3	C1→C2	C2→C3
	44%	39%	44%	39%	44%	39%
H1	78.8	17.2	44.1	11.2	24.4	12.4
H2	71.2	23.6	39.4	18.5	10.4	20.0
H3	37.3	28.4	12.9	21.5	7.0	11.8

Table 7: Increment percentage of the toe intrusion versus the increment percentage of the extraction rate

	C1		C2		C3	
	Q1→Q2 140%	Q2→Q3 110%	Q1→Q2 140%	Q2→Q3 110%	Q1→Q2 140%	Q2→Q3 110%
H1	30.8	14.7	5.4	-1.0	0.0	0.0
H2	26.9	16.7	3.4	-7.6	-0.9	-6.4
H3	18.6	1.4	-2.5	-3.8	-7.7	-11.5

saltwater toe intruded the porous media about 50 cm, 60 cm and 75 cm in C1, C2 and C3 experiments respectively. Namely, increasing the saltwater concentration by 44% and 39% caused the toe to move 22% and 25% more than before respectively. It demonstrates that in a higher saltwater concentration, increasing the concentration had more effect on the toe intrusion. Table 6 quantifies the saltwater concentration effect in the extraction condition for all the experiments. As shown in Table 6, in discharge rate of Q1, increment percentage of the movement due to concentration change in a high concentration (C2→C3) was more than in a low concentration (C1→C2). In addition, when H was deepened, this increment percentage (IP) was decreased in C1 and increased in C2. While in discharge rate of Q2 at the both well depths of H1 and H2, the increment percentage was higher in low concentration of the saltwater (C1→C2) relative to the high concentration of saltwater (C2→C3), but in Q2H3, an opposite trend was observed. Besides, when H was deepened, the IP was decreased in C1 and increased in C2 (similar to Q1). In Q3H1, in the low concentration (C1→C2), the IP was more than in the high concentration (C2→C3) but in Q2 (H2, H3), an opposite trend was obtained. Also, when H was deepened, the IP was decreased in C1 and had erratic behavior in C2. Generally, when the Q was increased, the IP was decreased. Eventually, it can be concluded that, when the Q and H were increased, the IP of C for the toe position was decreased. The rate of the IP in a low concentration was more than that in a high concentration.

Table 7 quantifies the extraction rate effect on the toe position for all the experiments. As shown in Table 7, in a higher extraction rate, increasing the Q had less effect on the toe intrusion. When the C was increased, the IP of the Q was significantly decreased, even in some scenarios, the IP became negative. It means that the toe moved backward. In

addition, increasing the H, had the same effect as the C. Overall, it can be say that in a high C and Q values and when the H was deepened, increasing the Q had less effect on the toe intrusion and in some scenarios the toe moved backward.

## CONCLUSION

It is impractical to investigate the effects of different factors variations on saltwater behavior in a field scale study of coastal aquifers. Therefore, a laboratory box can be a suitable method to consider these effects. The effects of saltwater concentration, well depth and well extraction rate variations on saltwater wedge behavior through an experimental box were analyzed. In addition, for numerical study of the processes, the SEAWAT model was used to simulate the experimental results and in obtaining detailed and extra information about the experiments. Results showed that increasing the concentration made the saltwater wedge move a further distance and the saltwater wedge at the inlet chamber moved slightly downward. Also, in a higher saltwater concentration, increasing the concentration had more effect on the toe intrusion. Analysis of the extraction rates showed that when the Q rate was increased, the saltwater reached the well sooner and the extracted water salinity reached a constant value in a longer time and the final constant concentration were increased. Investigating the well depth variations demonstrated that when the well was deepened, the salinity of the extracted water reached a constant measure in longer times and the final constant concentration were increased. Studying the combined effects of the factors showed that when the well was deepened enough and the extraction rate was high, the well behaved like a barrier and prevented the saltwater wedge to move further. Also, in a deeper H conditions, changing the C had a minor effect on the toe position. Analysis of the velocity vectors obtained from SEAWAT showed that when

the well was shallow and the extraction rate was big enough, almost no freshwater reached the top of saltwater chamber to overflow.

## ACKNOWLEDGEMENT

This study was carried out in Department of Water Engineering, Faculty of Agriculture, University of Tabriz as a PhD thesis. Financing the project was undertaken under the PhD course financial terms.

## CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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#### **HOW TO CITE THIS ARTICLE**

Noorabadi, S.; Nazemi, A.H.; Sadraddini, A.A.; Delirhasannia, R., (2017). Laboratory investigation of water extraction effects on saltwater wedge displacement. *Global J. Environ. Sci. Manage.*, 3(1): 21-32.

**DOI:** [10.22034/gjesm.2017.03.01.003](https://doi.org/10.22034/gjesm.2017.03.01.003)

**url:** [http://gjesm.net/article\\_22635.html](http://gjesm.net/article_22635.html)

