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Laboratory and numerical investigation of salinity infiltration in open coastal aquifers: A case study of Bandar Abbas

Sina Mohamad Pour[1,*], Reza Abdi[2], and Mohammad Reza Naseri[3]

[1]Payame Noor University, Jask branch, Hormozgan, Iran

[2]Payame Noor University, Bushehr branch, Iran

[3]Payame Noor University, Chabahar branch, Sistan and Baluchestan, Iran

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Abstract

Saline intrusion into coastal aquifers is one of the major challenges in groundwater resource management in coastal areas. In this study, the behavior of salinity intrusion in the open coastal aquifer of Bandar Abbas has been investigated using a laboratory model and numerical simulation. The SEAWAT numerical model was used to simulate the flow and transport of salinity. The results showed that the numerical model has a high ability to predict the location of the salinity tongue and is in good agreement with the laboratory data. The effects of various factors such as shore slope, initial concentration, and time on the spread of salinity were also analyzed.

Keywords: Salinity intrusion; Open coastal aquifer; Bandar Abbas; SEAWAT model; Sand flume; Salt transport.

1. Introduction

Coastal aquifers are exposed to salinity intrusion due to their proximity to saltwater sources such as seas. This phenomenon is especially important in arid and semi-arid regions such

* Corresponding Author's Email: s.mpour@gmail.com

as southern Iran, which are highly dependent on groundwater resources. Increased groundwater extraction and sea level rise are factors that exacerbate this phenomenon. Bandar Abbas, as one of the important coastal cities of Iran, faces the risk of salinity intrusion due to the challenges of population growth, industrial development, and excessive extraction of groundwater resources. In recent decades, population growth, urban development, and increased demand for freshwater resources in coastal areas have put great pressure on groundwater aquifers. This pressure, especially in arid and semi-arid regions such as southern Iran, has caused excessive extraction of aquifers and, as a result, a decrease in groundwater levels. One of the important consequences of this phenomenon is the intrusion of salt water from the sea into coastal aquifers, which is called "salinity invasion" (Bear *et al*., 1999). Salinity invasion not only reduces the quality of water resources, but also poses a serious threat to agriculture, public health, and sustainable development in coastal areas. Bandar Abbas, as one of the important coastal cities of Iran, with a population of over 600,000 and extensive industrial activities, is highly dependent on groundwater resources. Studies have shown that in some areas of this city, the electrical conductivity of groundwater has reached more than 4,000 microns/cm, indicating significant salinity intrusion (Salehi *et al*., 2023). In such circumstances, accurate understanding of the process of salinity intrusion and prediction of its behavior in aquifers is an undeniable necessity for water resources management.

Numerical modeling and physical experiments are two complementary tools for analyzing this phenomenon. Numerical models such as SEAWAT, by simulating water flow and salt transport, allow for the examination of different scenarios and the evaluation of management strategies (Guo and Langevin, 2002). Several studies have been conducted at the global and national levels on salinity intrusion in coastal aquifers. Akbarpour *et al*. (2024) used the SEAWAT model to investigate the advance of saltwater in a sloping sandy aquifer and showed that the numerical model performs well in transient conditions and that increasing the slope reduces salinity intrusion. Bear *et al*. (1999) presented one of the first conceptual models of salinity intrusion, which was based on the hydrostatic equilibrium between saltwater and freshwater. Later, more advanced numerical models such as SEAWAT were developed that allowed for the simultaneous simulation of water flow and salt transport (Guo and Langevin, 2002). Also, Mehdizadeh Mahali and Vafaei (2021) investigated the behavior of salinity infiltration in open coastal aquifers in a laboratory study using the SEAWAT model and measured the thickness of the transition zone with 5% and 95% co-concentration lines, compared it with the numerical model, and showed that this model performs well in stable conditions.

Ghorbanpour Landi *et al*. (2018) showed in the Babol Rud Plain, using field data and numerical modeling, that excessive extraction of aquifers was the most important factor in salinity in that area. Javadi and Kardan Moghadam (2019) also investigated the performance of the SEAWAT model in complex conditions using 3D simulation in desert aquifers and obtained acceptable results. International studies have also shown that the use of numerical models alongside laboratory data can be a powerful tool for water resources management. Especially in areas where field data are limited, numerical modeling allows for the analysis of different scenarios (Barlow and Reichard, 2010).

2. Data and method

2.1. *Study Area*

The study area is the Isin Plain of Bandar Abbas, which is adjacent to the Persian Gulf. This plain with geographical coordinates of longitude and latitude of 27.32, and 56.28 respectively. has a free aquifer with an average thickness of 30 m and a natural slope of about 2% towards the sea. Hydrogeological data show that the electrical conductivity of groundwater in some places has reached more than 4000 microns/cm.

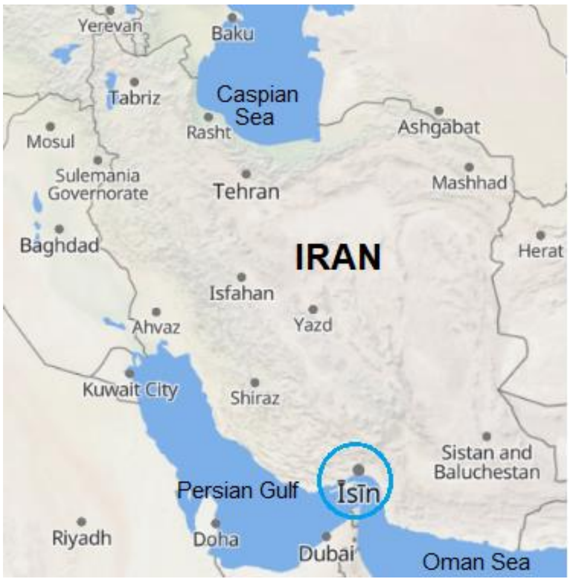

Figure 1. Study area. Isin, Hormozgan, Iran.

2.2. *Laboratory model*

To investigate the behavior of salinity intrusion under controlled conditions, a physical model was designed in the form of a sand flume with dimensions of 2 m long, 0.5 m wide and 0.5 m high. The flume walls were made of transparent plexiglass to allow direct imaging and observation of the salinity front. The flume bed was filled with uniform sand with a uniformity coefficient Cu=1.8C_u = 1.8 and a curvature coefficient Cc=1.2C_c = 1.2. The average porosity of the sand was measured to be 0.35 and its permeability coefficient was about $1.2\times10{-}4$ m/s. On the left side of the flume, a saltwater tank with a concentration of 35 g/l (simulating Persian Gulf water) was placed, and on the right side, a freshwater tank with a concentration of zero was placed. The position of the salinity tongue and the transition zone were recorded using concentration sensors and image processing techniques. Electrical conductivity sensors and image processing techniques were used to record the position of the salinity tongue. Data were recorded at 6-hour intervals for 48 hours.

2.3. SEAWAT numerical model

The SEAWAT model was used to simulate water flow and salt transport. Laboratory-like boundary conditions were defined and initial data were extracted from experiments. The model was run in two steady and unsteady states. This model, which is a combination of MODFLOW for groundwater flow and MT3DMS for mass transfer, was used for numerical simulation (Guo and Langevin, 2002). The numerical grid consisted of 200 cells in the longitudinal direction and 20 cells in the vertical direction. The boundary conditions were defined similar to those in the laboratory (Table 1):

- Inlet boundary: constant flux of saline water with a concentration of 35 g/L.
- Outlet boundary: constant flux of freshwater with a concentration of zero.
- Upper and lower boundaries: no-flow Physical parameters of the model included.

Table 1. Different coefficient resulted from the model

Parameter	Unit	Amount
Effective analysis	_	0.35
Permeability coefficient	m/s	1.2×10^{-4}
Longitudinal diffusion coefficient	m	0.1
Transverse diffusion coefficient	m	0.01
Depth diffusion coefficient	m	0.005

2.4. Model Validation

To validate the numerical model, the simulation results were compared with the experimental data. The evaluation criteria included:

- The position of the salinity tongue at different times
- The thickness of the transition zone between the 5% and 95% isoconcentration lines
- The time to reach steady state
- The relative error between the numerical model and the experimental data was calculated using the RMSE criterion.

3. Results

3.1. Experimental Results

The salinity tongue gradually advanced in the flume and reached a steady state after about 48 hours. The thickness of the transition zone between the 5% and 95% isoconcentration lines was measured to be about 15 cm. During the experiment, the position of the salinity tongue was recorded at different times. The Table 2 shows the position of the salinity tongue over time.

Table 2. Salinity tongue position upon time variation

Salinity tongue position (centimeters)	Time (hour)
0	0
25	6
45	12
70	24
85	36
90	48

The following graph shows the trend of progress of salinity in a laboratory flume:

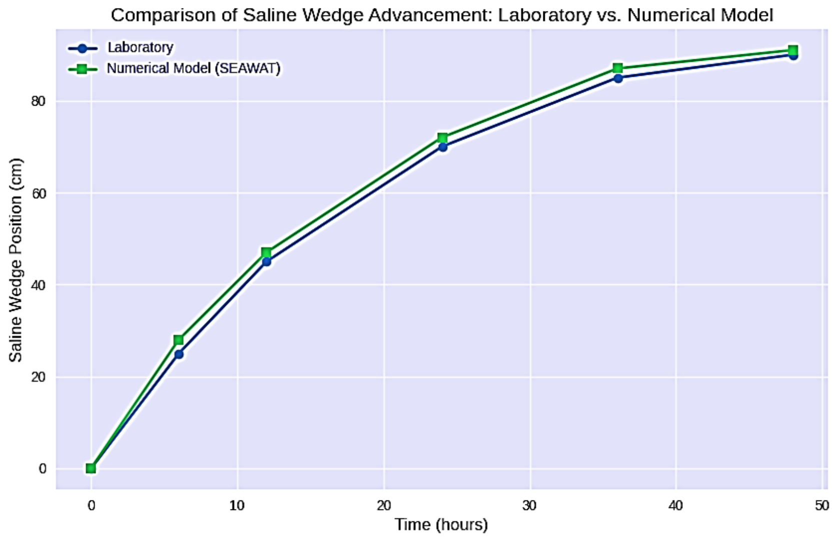

Figure 2. Comparison of saline wedge advancement: Laboratory vs. Numerical Model

Figure 2 shows saline wedge position (cm) in different periods. Two curves represent; Laboratory data (based on physical flume experiment), and Numerical model (SEAWAT simulation). Analysis of the “Salinity Tab Advancement in the Laboratory Flume” and its results shows that:

- General trend: Both curves show an increase in the salinity tab position over time, but the numerical model is slightly ahead of the laboratory data at each stage.
- Final difference: At 48 hours, the numerical model predicted a position of 91 cm, while the laboratory recorded 90 cm.
- Transition zone thickness: The numerical model predicted a thickness of 17 cm, while the laboratory measured 15 cm — a difference of about 13%. Initial advance rate: In the early hours (up to 12 o’clock), the advance rate is faster and then approaches a steady state.

3.2. Results of the SEAWAT numerical model

The SEAWAT model was used to simulate the flow and transport of salt. The boundary conditions were defined similar to those in the laboratory. The numerical grid consisted of 200 cells in the longitudinal direction and 20 cells in the vertical direction. The simulation time was considered to be 48 hours and the initial data were extracted from the experiments. The SEAWAT model was able to predict the position of the salinity tongue with reasonable accuracy. The relative error between the numerical model and the laboratory data was calculated using the RMSE criterion and its value was reported to be less than 10%. Also, the time to reach the steady state was approximately equal in both models. In addition, the thickness of the transition zone in the numerical model was about 17 cm, which is in acceptable agreement with the laboratory value (15 cm). The position of the salinity tongue in the numerical model was as stated in Table 3.

Table 3. Salinity tongue by the numerical model upon different time step

Salinity tongue position (centimeters)	Time(hour)
0	0
28	6
47	12
72	24
87	36
91	48

3.3. Sensitivity analysis

In this section, the effect of changes in the slope of the coast, the initial saltwater concentration and the freshwater recharge rate on the location of the salinity tongue was investigated. The results showed changes in the following three key parameters:

- Slope of the coast: Increasing the slope from 2% to 5% reduced the salinity intrusion by 20%.
- Saline concentration: Increasing the concentration from 35 to 50 g/l increased the thickness of the transition zone by 25%.
- Freshwater recharge rate: Reducing the recharge rate caused the salinity tongue to advance further towards the land.

These results indicate that engineering design and water resources management can play an effective role in controlling salinity intrusion.

4. Discussion

The comparison of the results showed that the SEAWAT numerical model is a suitable tool for simulating salinity intrusion in coastal aquifers. However, in unstable conditions, the numerical model tends to over-predict the expansion of the salinity tongue, which requires more accurate calibration. The results of physical experiments and numerical modeling showed that salinity intrusion in open coastal aquifers is affected by several factors, including shore slope, saltwater concentration, and freshwater recharge rate. The SEAWAT model was able to predict the location of the salinity tongue with reasonable accuracy, and the difference between numerical and experimental results was less than 10%. Similar studies in Iran also confirm these findings. For example, Akbarpour *et al*. (2024) showed that increasing shore slope reduces salinity intrusion. Also, Ghorbanpour Landi *et al*. (2018) found in the Babol Rud plain that excessive abstraction of aquifers was the most important factor in salinity intrusion in that region. Internationally, Barlow and Reichard (2010) emphasized that numerical modeling, along with field data, is a powerful tool for managing water resources in coastal areas. Guo and Langevin (2002) also developed the SEAWAT model, which allowed for simultaneous simulation of flow and salt transport, which was also used in this study. From a management perspective, the results of this study show that controlling the withdrawal rate, increasing artificial recharge, and designing impoundment structures can play an effective role in reducing salinity intrusion (Zohrabi *et al*. 2022). Also, continuous monitoring of groundwater quality and the use of numerical models to predict future scenarios are requirements for sustainable water resources management.

Conclusion

The present study showed that the combination of physical experiments and numerical modeling can provide a better understanding of the salinity intrusion process in open coastal aquifers. The use of the SEAWAT model in the management of groundwater resources of Bandar Abbas is recommended. In this study, the behavior of salinity intrusion in the open coastal aquifer of the Isin Plain of Bandar Abbas was investigated using a sand flume laboratory model and numerical simulation with the SEAWAT model. The results showed that:

- The SEAWAT model has a high ability to predict the location of the salinity tongue.
- The difference between the numerical and experimental results was less than 10%.
- The thickness of the transition zone in the numerical and experimental models was in acceptable agreement.
- The slope of the shore, the concentration of saline water, and the rate of freshwater recharge are key factors in controlling salinity intrusion.

A comparison of the numerical and experimental results showed that the SEAWAT model performs well in steady-state conditions, but requires more accurate calibration in transient conditions. Also, the effect of coastal slope as an important factor in controlling salinity intrusion should be considered in engineering designs. It is suggested that future studies should also examine the effects of climate change, sea level rise, and different management scenarios. Also, the use of 3D models and more extensive field data can increase the accuracy of predictions.

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