An Experimental Study on Investigating and Controlling Salt Wedge Propagation

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Abstract. This study aims to investigate the variation of profiles and propagation of salt wedge. It also aims to investigate the use of air and water curtains in controlling its propagation. A laboratory flume system was prepared to simulate the propagation of the salt wedge. Relations between the profiles and propagation of salt wedge and the discharge of fresh water, longitudinal slope of bed of flume, the concentration of the salt, and the depth of salt water were obtained and analysed. Seventy-seven experiment runs were carried out to investigate the propagation of salt wedge. Moreover, a set of sixteen experimental runs were conducted to investigate controlling the salt wedge using air or water curtains. It was found that by increasing the discharge of fresh water or the slope of the flume bed leads to a reduction in the length of the salt wedge. This reduction reached a maximum percentage of 95%. The propagation of the salt wedge varies proportionally and linearly with the concentration of salt water and its variation with depth of salt water follows a power function. Furthermore, a maximum reduction of 87% was achieved in the salt wedge propagation when the EC is reduced by about 49%. The salt wedge propagation was reduced by 95.3% when the salt water depth reduced by 40%. It was found that both of the air and water curtains are efficient methods in controlling the propagation of salt wedge. A minimum discharge of air or water curtains to prevent the propagation of the salt wedge was obtained.

1. Introduction
Propagation of salt wedge into rivers is an interesting natural phenomenon that occurs in most of estuaries around the world. Salt water propagates upstream from the river mouth is affected by many factors such as discharge of fresh water, slope of river, height of tide, and concentration of salt water. The salt wedge can move along river bed to a long distance up the river due to the difference in densities. For example, the salt wedge in Shatt Al Arab River can reach Basrah City, south of Iraq, which is located at about 130 km upstream the river mouth at the Arabian Gulf. Salt wedge propagation causes deterioration of water quality of the river and makes it unsuitable for drinking and irrigation.

In addition, literature based on laboratory model studies to understand the propagation of salt wedge goes back to the fifties of the past century. Farmer [1] conducted experiments on salt wedges with the objective of understanding tidal flushing over a wide range of flow conditions using an experimental apparatus. In this study, a stationary salt wedge was obtained by eliminating the effect of tides. Profiles of wedge were plotted using dimensionless coordinates which indicated that each wedge follows approximately a parabolic relation. Numerus laboratory experimental research was conducted to investigate the behavior of salt wedge propagation since that date by many researchers such as Sargent and Jirka [2], Gerhard and Jirka [3], Coates \textit{et al}. [4], Whyte [5], and Ibrahim \textit{et al}. [6]. These studies gave a great understanding of salt wedge behavior and its response to different conditions.

Other studies were carried out based on field observations of the propagation and shape of the salt wedge at rivers mouth by Isao and Morimasa [7], Isao \textit{et al}. [8], Qian \textit{et al}. [9], CEB [10], De \textit{Nijs et al}. [11], Haralambidou \textit{et al}. [12], and Reeder [13]. Different techniques were used to observe the
propagation and shape of the salt wedge. These studies described in details the case of the salt wedge intrusion in different rivers.

In addition, there are many studies that were conducted to investigate methods to control the propagation of salt wedge. These methods include constructing penetrant an inflatable dams or gates, sill across the riverbed, increasing the roughness of the riverbed, changing the river mouth geometry, and using air curtains. Previous experimental studies showed that the use of an air curtain to be a promising method for controlling salt wedge. In this method, compressed air is pumped to the flow from a perforated pipe placed on the river bed across the river cross section, forming a vertical air curtain which acts as a wall to the propagation of the salt wedge. For further details on controlling the salt wedge, one may refer to the studies conducted by Fagerburg and Alexander [14], Nakai. and Arita [15], Liu et al. [16], and Haralambidou, et al. [17].

Moreover, studies used different numerical simulation approaches integrated with field or experimental observations to investigate the salt wedge in rivers. The results of the numerical simulation showed a promising agreement with the observed certain flow conditions and can accurately obtain the shape of salt wedge in rivers and the rate of salt water movement. These conclusions can be found in Ralston et al. [18]. Krivavica and Ružič [19], Funahashil et al. [20], Hwang et al. [21], Ayres [22], Leung et al. [23], and Maicu et al. [24]. Zachopoulos et al. [25].

Finally, more studies are needed to specifically understand the effects of different conditions on the behavior of the movement of salt wedge and to provide important data for further investigations. Generally, this study aims to experimentally investigate the factors affecting this behavior at different discharges of fresh water, depths of salt water, longitudinal slope, and concentration of salt of the salt wedge. Moreover, this study aimed to investigate the use of air and water curtains in controlling its propagation upstream the rivers.

2. Description of the Experiments Flume System

Figure 1 shows the laboratory flume system installed at the hydraulic laboratory of the College of Engineering of the University of Baghdad. Figure 2 shows a schematic diagram showing top view of the flume system. The flume is of 600 cm in length, 25 cm in height, and has a width of 7.5 cm. The slope of the flume can be adjusted from 0.0% to 3.0%. For the purpose of measuring the profile of the salt wedge along the flume, scales have been installed at the outer side of the flume wall at 14 cm apart. Its upstream can be supplied by fresh water from a 1000 l tank at a maximum rate of 80 l/min. A wooden weir with a dimension of 10 cm in length, 7.5 cm in width, and a height of 9 cm is fixed at the downstream end of the flume. The height of the weir can be increased by adding pieces of wood of 1 cm in thickness to its base. The weir is used to discharge water out of the flume to a basin at its end and to supply and retain salt water to a level that simulates the sea water level. Salt water is supplied to the flume through an opening of 1.9 cm at the center of the wire. The opening is connected by using a 1.9 cm hose to a constant head salt water reservoir. This reservoir has a dimension of 30 cm in length, 22 cm in width, and a height of 20 cm. So, the depth of water inside the reservoir is kept constant at 15 cm by draining out excess water from the reservoir through an opening of 1.27 cm in diameter at its side. The constant head reservoir is fixed on an adjustable level support. This reservoir has an inlet at its bottom connected to 500 l capacity salt water tank. Salty water is pumped from this tank to the constant head reservoir by using a 1.9 cm hose and is controlled by using a gate valve. After that, the level of the support of the constant head reservoir is adjusted to a level that maintains the level of salt water within the reservoir to be same as the freshwater level at the downstream end of the flume.

Then, salt water was prepared by adding a specified weight of salt, NaCl, to the water of the saltwater tank with a well mixing. Then, the electric conductivity (EC) of the salt water within the tank was tested. Depending on the tested EC value, concentration of salt water within the tank was adjusted by adding NaCl until reaching the required EC value to be included in the experiment. To clearly distinguish the profile and propagation of the salt wedge along the flume, it was found that an
approximately 5 to 10 gm of Potassium permanganate when added to the solution within the salty water tank dyes it with a clear purple color and makes it easy to trace the profile of the salt wedge.

Furthermore, to produce water or air curtain and to prevent the propagation of salt wedge, a perforated metal pipe of 8 mm in diameter with a T shape was used as in figure 3. One of pipe ribs has seven openings with 1 mm in diameter and 1 cm apart. A tube was used to connect the pipe to the air compressor or a water tap and is controlled by a valve. Water and air flow meters were used to measure the discharge of the water or air flow.

In the experiments to investigate the effect of the saltwater depth variation on the propagation of salt wedge, the saltwater depth was increased by increasing the height of the weir by adding pieces of wood of 1 cm in thickness each time. After reaching stationary state of salt wedge propagation, the salt wedge profile was recorded at each salt water depth.

Seventy-seven experiment runs were carried out to investigate the propagation of salt wedge under different discharges of fresh water, longitudinal slope of the flume, concentration of salt, and the supplied salt water depth. In these experiments, the discharge of fresh water varied between 17 and 80 l/min, the longitudinal slope of the flume varied between 0.0 and 3.0%, the upper range was used to amplify the effects of the slope, the supplied salt water levels ranged between 6 and 12 cm, and the EC of salt water varied between 30 and 60 ms/cm, which is within the range of salinity of seawater. The EC of the tested fresh water samples were too close with an average of 1.06 ms/cm.

Figure 1. The experimental flume system.

Figure 2. A top view schematic diagram of the flume system.
In addition, in the experiments to investigate the effectiveness of air or water curtain in controlling the propagation of salt wedges within the flume under certain conditions of flow, slope of the flume, and concentration of salt, the air or water diffuser was fixed on the flume bed. The flow of air or water out of the diffuser was increased by using a gate valve until reaching a minimum value of the discharge that can fully prevent the propagation of salt wedge at the location where it was fixed. Water or air discharges of the diffuser were measured using water and air meters, respectively. A set of sixteen experimental runs were conducted to investigate controlling the salt wedge using air or water curtains with an average of a constant fresh water of 45 l/min, the bed slope of flume of 0.0%, 9 cm weir height, and the EC of the salt water was about 50 ms/cm. The air or water diffusers were installed at eight different locations along the salt wedge, between 20.5 and 272.5 cm from the weir, to achieve the optimum discharge that prevents the salt wedge from run over the diffuser.

3. Results and Analysis
In all experiment runs, the salt wedge propagation occurred when the flow of salt water entered the flume at its downstream end always beneath the flowing fresh water, due its greater density, and appeared to be laminar. The salt water moves in the direction of upstream end of the flume to a distance at which the wedge is fully established and remains stationary. This distance depends on the applied discharge of fresh water, longitudinal bed slope of the flume, the concentration of salt water, and the depth of salt water, figure 4. It was noticed that breaking waves were formed along the interface between the wedge and the fresh water. The amplitude of these waves was increased in the downstream end direction of the flume, the deeper portion of the salt wedge. As a result of these waves, transporting of salt water occurs along interface to the downstream end direction of the flume.

3.1. Effects of the Fresh Water Discharge and the Flume Longitudinal Slope on the Salt Wedge Propagation
The profiles of stationary wedge were observed under different discharges of fresh water and longitudinal slope of the flume. The bed longitudinal slope of the flume was varied between 0.0% and 3.0%. At each specified slope of flume bed, the discharge of fresh water was varied in a range depending on the slope value. The maximum limit of this range was the same for all of the used longitudinal slopes of about 80 l/min. At the low applied discharges of fresh water with small bed slope of the flume, the propagation of salt wedge can exceed the total length of the flume. Therefore, the minimum limit of applied range of fresh water discharge was selected in such a way that the salt wedge was not allowed to reach the upstream end of the flume. For longitudinal slope of the flume bed of 0.0%, the minimum applied fresh water discharge was 45 l/min. While, for slopes of 0.25%,
0.5%, 0.75% and 1.0%, the minimum applied fresh water discharge was 38 l/min, and that for slopes of 1.25%, 1.5%, 2.0%, 2.50%, and 3.0% was 18 l/min.

**Figure 4.** Snap shots showing examples of the stationary salt wedge under different conditions.

Total salt water depths at the measuring points along the wedge were measured from the bed surface of the flume to the interface surface between the fresh water and the salt water. The interface surface is not steady due to the breaking waves. Therefore, interface surface was estimated to be in trough of the internal waves.

Figures 5 to 14 show the profiles of the salt wedge under deferent conditions of discharge of fresh water and slope of bed flume. In general, the increase of discharge of fresh water under the same slope of the flume bed and vice versa, the salt wedge length was reduced. The reduction in the length of salt wedge due to change of both discharge of fresh water and of flume bed slope is nonlinear.

In addition, the maximum propagation of the salt wedge of 438 cm was observed under the lowest applied discharge of 18 l/min and a bed slope of the flume was 1.25%. while, the minimum propagation of 24 cm was observed at the highest applied discharge at that slope of 79.8 l/min and bed slope of 3.0%. This is a percentage of about 95% reduction in the propagation of salt wedge.

Moreover, the stationary salt wedge has a concave profile and then reversed to a convex at the deep end of the wedge. At low fresh water discharge and small bed slopes of the flume, three quarter of the salt wedge was a concave profile and one quarter was the convex profile. The convex profile of salt wedge tends to diminish when the propagation of the salt wedge was reduced due to the increase in the discharge of the fresh water and the longitudinal slope of the flume. At high applied discharges and bed slopes of the flume, the profile of the salt wedge was only concave.

**Figure 5.** Variation of the salt wedge profiles with fresh water discharge, slope of flume equal to 0.0%.
Figure 6. Variation of the salt wedge profiles with fresh water discharge, slope of flume equal to 0.25%.

Figure 7. Variation of the salt wedge profiles with fresh water discharge, slope of flume equal to 0.5%.

Figure 8. Variation of the salt wedge profiles with fresh water discharge, longitudinal slope of flume equal to 0.75%.

Figure 9. Variation of the salt wedge profiles with fresh water discharge, slope of flume equals to 1.0%.

Figure 10. Variation of the salt wedge profiles with fresh water discharge, slope of flume equal to 1.25%.
Figure 11. Variation of the salt wedge profiles with fresh water discharge, slope of flume equal to 1.5%.

Figure 12. Variation of the salt wedge profiles with fresh water discharge, slope of flume equal to 2.0%.

Figure 13. Variation of the salt wedge profiles with fresh water discharge, slope of flume equal to 2.5%.

Figure 14. Variation of the salt wedge profiles with fresh water discharge, slope of flume equal to 3.0%.

Figures 15 and 16 show the effects of the discharge of the fresh water and the longitudinal slope of the flume on the propagation of the salt wedge, respectively. It seems that the discharge and the slope of the flume have nested effects on the propagation of the salt wedge. When slope of the flume was fixed to a certain value, it was noticed that the propagate of the salt wedge reached a distance of just about 24 to 27 cm at high applied discharges of fresh water in all of the examined slopes. As the discharge of the fresh water and the slope of the flume were reduced, the propagation of the salt wedge was proportionally increased. As a result, this increase occurs at a nonlinear rate that depends on the reduction of both slope and discharge of the fresh water.
$R^2 = 0.93$

Figure 15. The relation between the fresh water discharge and the salt wedge propagation.

Figure 16. The relation between the flume longitudinal slopes and the salt wedge propagation.

Power function relations, $p = a d^b$, with good correlation coefficients, $R^2$, of a range of 0.99 to 0.93 with an average of 0.96, were obtained between the salt wedge propagation, $p$, and the discharge of the fresh water, $d$, for each of the longitudinal slope of the flume, Figures 17 and 18.

Figure 17. The relation between the salt wedge propagation and the fresh water discharges under different flume longitudinal slope, bed slope 0.00 to 1.25%.
3.2. Effects of the Concentration of Salt Water on the Propagation of Salt Wedge

The experimental runs were carried out to investigate the effect of the concentration of salt, represented by the EC of the salt water, on the propagation of salt wedge. In these runs, the discharge of fresh water and the bed slope of the flume were set to be constant at 45 l/min and 0.0%, respectively. The range of the EC of the salt water was varied between 30 to 60 ms/cm. The EC values of the fresh water samples, i.e., tap water, when carrying out these runs were too close with an average of 1.14 ms/cm.

Figure 19 shows the variation of the salt wedge profile with the variation of EC values of salt water. It is clear that the concentration of salt has a great effect on the propagation of salt wedge. The maximum propagation was 510 cm at EC value of 60 ms/cm and the minimum was 64.5 cm for EC value of 30.5 ms/cm, this forms a reduction of 87% in the salt wedge propagation.

Figure 20 shows the variation of salt wedge propagation with the variation of the EC values. The propagation of salt wedge varied proportionally and linearly with the EC values. The linear relation was obtained with a correlation coefficient of 0.99.

Figure 18. The relation between the salt wedge propagation and the fresh water discharges under different flume longitudinal slope, bed slope 1.25 to 3.00%.

c. Bed slope = 1.5%.
d. Bed slope = 2%.
e. Bed slope = 2.5%.
f. Bed slope = 3.00%.

Figure 19. Variation of salt wedge profiles with the EC of salt water.

Figure 20. The Relation between salt wedge propagation and the EC of salt water.
3.3. Effects of Applied Salt Water Depth on the Salt Wedge Propagation

The propagation of the salt wedge was investigated under different values of applied salt water depth. The applied salt water depth was changed by changing the height of the weir and the salt water level in the constant head reservoir. In the experimental runs, the discharge of fresh water, the longitudinal slope of the flume bed, and the EC of salt water were kept constant at about 45 l/min, 0.0%, and 50 ms/cm, respectively. The initial height of the weir was 6 cm then increased to 10 cm by an increment of 1 cm. Figure 21 shows the variation of the salt wedge profile with the variation of the weir height. Generally, changing the depth of salt water had a great effect on the salt wedge propagation; the propagation increased from 20 cm at weir high of 6 cm up to 430 cm at a weir height of 10 cm, this forms 95.3% reduction when the salt water depth reduced by 40%.

![Figure 21](image1.png)

Figure 21. Variation of salt wedge profiles with the depth of salt water.

Figure 22 shows clearly that the variation of the salt wedge propagation with salt water depth follows a power function. This relation was obtained with a correlation coefficient of 0.97.

![Figure 22](image2.png)

Figure 22. The relation between the salt wedge propagation and the salt water depth.

3.4. Controlling of Salt Wedge by using Air and Water Curtains

The salt wedge propagation was investigated under different values of salt water depths. The applied salt water depth was changed by changing the height of the weir and the salt water level in the constant head reservoir. So, in the experimental runs, the discharge of fresh water, the longitudinal slope of the flume bed, and the EC of salt water were kept constant at about 45 l/min, 0.0%, and 50 ms/cm, respectively.

3.4.1. Controlling the salt wedge propagation by using an air curtain

The minimum required air flow discharge through the diffuser installed at eight different locations, figure 23, that can fully prevent the salt wedge propagation were observed and plotted as shown in figure 24. Generally, the propagation of salt wedge could be prevented at any location in all of the experimental runs by using the air curtain with an optimum discharge of air at that location. The range of the minimum required air discharge varied between 1.5 l/min, when the air diffuser was located at a distance of 20.5 cm from the weir, and 0.25 l/min, when the air diffuser was located at a distance of 272.5 cm from the weir. This forms a difference of 83% in the required air discharge between the two locations. The relation between the minimum required air discharge and the location of the air diffuser was obtained that takes a power function form with a correlation coefficient of 0.99, Figure 24.

Accordingly, the minimum value of air discharge required to prevent the salt wedge propagation was increased as going towards the downstream side of the flume, toward the weir, because of increasing depth of salt water. Increasing the salt water depth in turn increases the intrusion force of a
salt wedge, so the mixing due to the turbulence caused by the air curtain should increase in order to overcome the intrusion force and prevent salt wedge from being intrusion downstream of air diffusers.

![Figure 23](image-url)

**Figure 23.** A snapshot showing the air curtain.

![Figure 24](image-url)

**Figure 24.** The minimum required diffuser air discharge.

3.4.2. **Controlling the salt wedge propagation by using a water curtain.** As in the use of air curtain, the propagation of salt wedge could be prevented at any location by using the water curtain with an optimum discharge of water at that location. The difference between using the air curtain and the water curtain in controlling the salt wedge propagation is referred to the difference in properties between the two fluids. Water has a density and viscosity much higher than that of water. For the same discharge value, it is expected to have more turbulence that leads to more mixing between the salt and fresh water. In addition, the supplied fresh water through the diffuser is mixed directly with the salt water that leads to dilute that concentration of salt. This property doesn’t exist when using the air curtain. The water curtain didn’t make turbulence and fluctuations in the fresh water surface as when using the air curtain, as shown in Figure 25. Thus, using of water curtain is more efficient than that of air in controlling the propagation of salt wedge.

![Figure 25](image-url)

**Figure 25.** A snapshot showing the water curtain.

The values of minimum required discharges of water through the diffuser installed at eight different locations that can fully prevent the salt wedge were presented in Figure 26. These values varied between 0.8 l/min, when the water diffuser was installed at a distance of 20.5 cm from the wire, and
0.41 l/min, when the water diffuser was installed at a distance of 272.5 cm. This forms a difference of about 49% in the required water discharge between the two locations. The relation between the minimum required discharge of water and the location of the air diffuser was obtained to be a power function form with a correlation coefficient of 0.99.

As in the use of water curtain, the minimum value of the discharge of water required to prevent the propagation of salt wedge was increased as going towards downstream side of the flume.

![Figure 26](image)

**Figure 26.** The minimum required water diffuser discharge.

### 4. Conclusion

From the results of the experimental runs, it was found that

1. The interface surface between the fresh and salt water is not in a steady state due the formation of breaking waves.
2. The propagation of salt wedge inversely related to the applied fresh water discharge and the slope of the flume. The maximum propagation of the salt wedge of 438 cm was observed under the lowest applied discharge of 18 l/min and a bed slope of the flume was 1.25%. while, the minimum propagation of 24 cm was observed at the highest applied discharge at that slope of 79.8 l/min and bed slope of 3.0%. This is a percentage of about 95% reduction in the propagation of salt wedge.
3. A power function relation was obtained with good correlation coefficients between the propagation of the salt wedge and the discharge of the fresh water for each of the longitudinal slopes of the flume that were applied.
4. The concentration of salt has a great effect on propagation of salt wedge. The propagation of salt wedge varied proportionally and linearly with the EC values. A reduction of 87% in the salt wedge propagation when the EC is reduced by about 49%.
5. The depth of salt water had a great effect on propagation of salt wedge. The variation of the propagation of the salt wedge with depth of salt water follows a power function. The propagation was reduced by 95.3% when the salt water depth reduced by 40%.
6. The propagation of salt wedge can be prevented at any location by using the air or water curtains.
7. The minimum value of air or water discharge required to prevent the propagation of salt wedge was increased as going towards the downstream side of the flume, toward the source of salt water.

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