Water Resources and Surveying Engineering

CFD Simulation Model of Salt Wedge Propagation

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ABSTRACT

This study aims to numerically simulate the flow of the salt wedge by using computational fluid dynamics, CFD. The accuracy of the numerical simulation model was assessed against published laboratory data. Twelve CFD model runs were conducted under the same laboratory conditions. The results showed that the propagation of the salt wedge is inversely proportional to the applied freshwater discharge and the bed slope of the flume. The maximum propagation is obtained at the lowest discharge value and the minimum slope of the flume. The comparison between the published laboratory results and numerical simulation shows a good agreement. The range of the relative error varies between 0 and 16% with an average of 2% and a root mean square error of 0.18. Accordingly, the CFD software is quite valid to simulate the propagation of the salt wedge.
Keywords: CFD, fresh-salt water mixing, numerical model, salt wedge intrusion,

ديناميكية الموائع الحسابية لتمثيل تداخل الموجة الملحية

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الخلاصة

تهدف الدراسة إلى محاكاة جريان الموجة الملحية باستخدام برنامج ديناميكية الموائع الحسابية (CFD). تم التحقق من النموذج العددي باستخدام بيانات النموذج المختبري المنشور. اجريت اثني عشر تجربة حول محاكاة التقدم الملحي تحت نفس الظروف المختبرية. اظهرت النتائج ان التقدم الملحي يسلك سلوكا عكسيا مع تصريف المياه العذبة وميل قعر القناة. يتم الحصول على اكبر مسافة للتقدم الملحي عند اقل تصريف وميل قعر القناة. اظهرت مقارنة النتائج المختبرية مع نتائج المحاكاة العددية توافق ممتاز. الخطأ النسبي يتراوح بين 0% و 16% وبمعدل 2% وجذر متوسط الخطا التربيعي 0.18. بعد اختبار نموذج CFD تم التوصل الى قدرة البرنامج على محاكاة تقدم الموجة الملحية.

الكلمات الرئيسية: تداخل الموجة الملحية ، خلط الماء المالح-العذب، ديناميكية الموائع الحسابية ، النموذج العددي.

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1. INTRODUCTION

The intrusion of the salt wedge into the estuaries of rivers is an important natural phenomenon that deteriorates the quality of water upstream the mouth of the rivers and negatively impacts different human uses and activities. This intrusion is affected by many factors, including the freshwater discharge, the slope of the bed, the roughness of the river, saltwater depth, and saltwater concentration. As an example, the Shatt Al-Arab River, Iraq, faced a significant increase in the salinity of water due to the propagation of salt wedge to about 130 km upstream of the river mouth reaching the Basrah City, which makes the river water unsuitable for drinking and irrigation, (**Al-Fuady and Azzubaidi, 2021).**

Studies investigating the behavior and understanding the propagation of salt wedge in rivers' mouths go back to (**Farmer, 1951)** who conducted experiments on the intrusion of salt wedges. Since that date, numerous field observations and laboratory experiments have been conducted to study the propagation of salt wedge. Many studies were conducted using different numerical simulations techniques of salt wedge intrusion at estuaries integrated with fields or laboratory experiments. These simulation techniques proved to be a promising tool for better understanding this phenomenon with detailed results. It agreed well with field or laboratory observation and can adequately obtain the intrusion of the salt wedge in rivers. (**Kobayashi et al., 2011)** conducted a field observation and numerical simulation of the salt wedge intrusion in the Tone River estuary, Japan. The major characteristic of the salt wedge movement collected by field observation were reproduced by using a vertical two-dimension abalone model with a k-ε model to simulate flow turbulence. (**Funahashi1 et al., 2013)** studied the effect of using the freshwater discharge of the Yura River estuary, Japan, on salt intrusion using the Delft3D- Flow model. The study proved that salt wedge propagation has a good agreement compared to the field observations. (**Ayres, 2015)** conducted a numerical investigation to evaluate the effect of salts in the Mississippi estuary on sediment transport using a Cartesian Z Coordinate Delft 3D numerical Model. The Z-model showed to have the ability to adequately obtain the propagation of salt wedge as observed in the prototype. (**Ralston et al.,2016)** conducted a study on the turbulent mixing of the salt wedge. They used a 3-D unstructured grid finite-volume hydrodynamic model (FVCOM). This model was validated against field observations. Model calibration was improved by optimizing both the threshold mixing within the turbulence closure and the bottom roughness**. (Hwang et al., 2017)** investigated the effects of tides on salt wedge and stratification of the Seomjin River Estuary, South Korea, under idealized conditions. They used a Finite Volume Coastal Ocean Model (FVCOM) to the type of stratification and controlled the estuary flow under different conditions. (**Maicu et al., 2019)** conducted a study on the factors affecting salt wedge propagation in the Po River Estuary, Italy. The numerical simulation was carried out using the mathematical model SHYFEM code. They calibrated and validated the model with a salinity profile taken along the river talweg. (**Krvavica and Ružić, 2020)** conducted a numerical simulation study on salt wedge propagation in idealized and Neretva River Estuary, Croatia. They used a two-layer shallow-water numerical model that proved reliable and accurate in obtaining the salt-wedge dynamics**. (Zachopoulos et al., 2020)** studied the effect of tides on salt wedge propagation along the Strymon River Estuary, Greece. To simulate the dynamics of a salt-wedge intrusion along the lower reach of the river upstream its mouth, Estuary Lake and Coastal Ocean Model (ELCOM) was used. The model was calibrated with field observations and offered fairly reliable results of salt wedge intrusion.

CFD has become an effective tool to study the hydrodynamic of fluid flow under different conditions with comprehensive details rather than relying on conducting time-consuming and costly field or laboratory experiments. The study aims at simulating salt wedge intrusion by using the ANSYS Fluent, CFD software under certain conditions and compared it with published laboratory experimental data.

2. THE DESCRIPTION OF THE PUBLISHED LABORATORY EXPERIMENTAL MODEL

To validate the simulation results of CFD software in simulating the salt wedge intrusion, the results of the experimental laboratory study (**Al-Fuady and Azzubaidi, 2021)** were used for comparison purposes. This experimental study was focused on investigating the factors affecting the behavior of salt wedge intrusion under different flow conditions of the depth of saltwater, discharges of freshwater, the concentration of salt, and the longitudinal slope of the bed of the flume. They prepared a flume to conduct the experiments, as shown by **Fig. 1.** The system consists of a flume of 6 m in length with an adjustable longitudinal slope supplied by freshwater from upstream. A weir of adjustable height is installed at the downstream side of the flume. This weir is used to discharge freshwater from the flume and supply saltwater through an opening at its center that connects a saltwater tank. This weir retains saltwater to a level that simulates the seawater level so that the depth of the saltwater is the depth measured from the bottom of the flume to the crest of the weir. To easily recognize the shape of the salt wedge, Potassium permanganate was added in a small amount to the saltwater that clearly dyes it with a purple color.

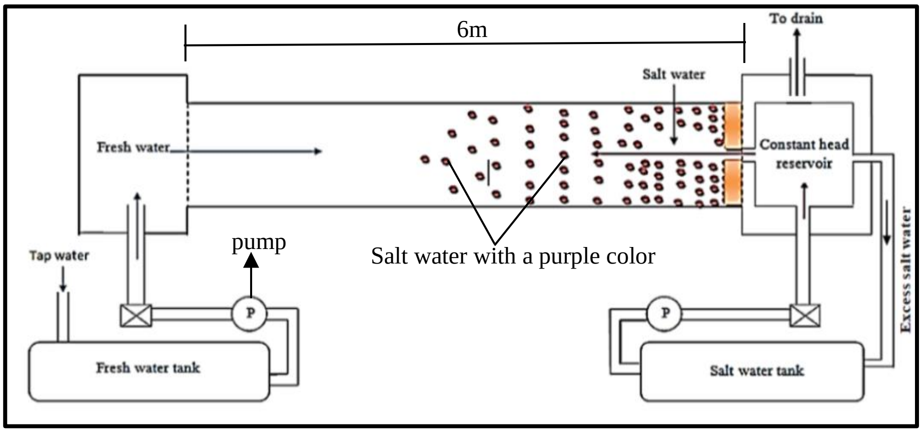


Figure 1. A top view schematic diagram showing the flume system **(Al-Fuady and Azzubaidi, 2021).**

They conducted seventy-seven experiments under different freshwater discharges, supplied saltwater depths, concentrations of salt, and slope of the flume. **Table 1** summarizes the applied parameters of the twelve runs selected runs for comparison with the runs of the numerical model.

Table 1. The parameters of selected experimental runs of (**Al-Fuady and Azzubaidi, 2021).**

Slope%	Fresh water		Salt water	
	Discharge, *l/min*	**Depth , *m***	**Depth, *m***	**Density, *kg/m³***
0%	45.3	0.12	0.09	1022.79
	55.6	0.13	0.09	1023.17
	78.4	0.16	0.09	1023.25
1%	45.1	0.06	0.09	1022.19
	61.3	0.07	0.09	1024.53
	78.6	0.08	0.09	1022.79
2%	17.4	0.05	0.09	1023.62
	55.9	0.06	0.09	1024.07
	79.9	0.06	0.09	1021.97
3%	45.9	0.03	0.09	1023.17
	54.6	0.04	0.09	1024.83
	72.6	0.05	0.09	1024.53

3. THE CFD MODEL

CFD has become a common and efficient tool to study the hydrodynamics of fluids flow under different conditions with comprehensive details to avoid depending on field or laboratory experiments which consume time and money. ANSYS CFD solves numerically the governing equations the Navier-Stokes and the continuity equations (**Versteeg and Malalasekera, 2007).** The Navier-Stokes equations are:

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial w}{\partial z}\right)=\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)+\rho g_x-\frac{\partial p}{\partial x} \quad (1)$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial w}{\partial z}\right)=\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+\rho g_y-\frac{\partial p}{\partial y} \quad (2)$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial w}{\partial z}\right)=\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+\rho g_z-\frac{\partial p}{\partial z} \quad (3)$$

Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (4)$$

Where:

u , v, w= velocity vector in three direction, *m/s*.

ρ = density, kg/m^3.

μ = dynamic viscosity, $N.s/m^2$.

P = pressure, *Pa*.

g = gravitational acceleration, m/s^2.

Turbulent standard k-ε model was selected and used by the software to simulate flow turbulence (**Versteeg and Malalasekera, 2007).**

This study defined the boundary conditions as a velocity inlet and a pressure outlet. The air velocity above the water surface was set to zero as an initial boundary condition.

Generally, the stages in simulating the fluid flow in the CFD are to draw the geometry model in all the details, divide the model into small cells and define boundary conditions, the definition of materials used, solving for the results.
All the geometry of the flume fabricated by (**Al-Fuady and Azzubaidi, 2021)** was defined in detail using SOLDWORK2018, as shown in **Fig. 2**.

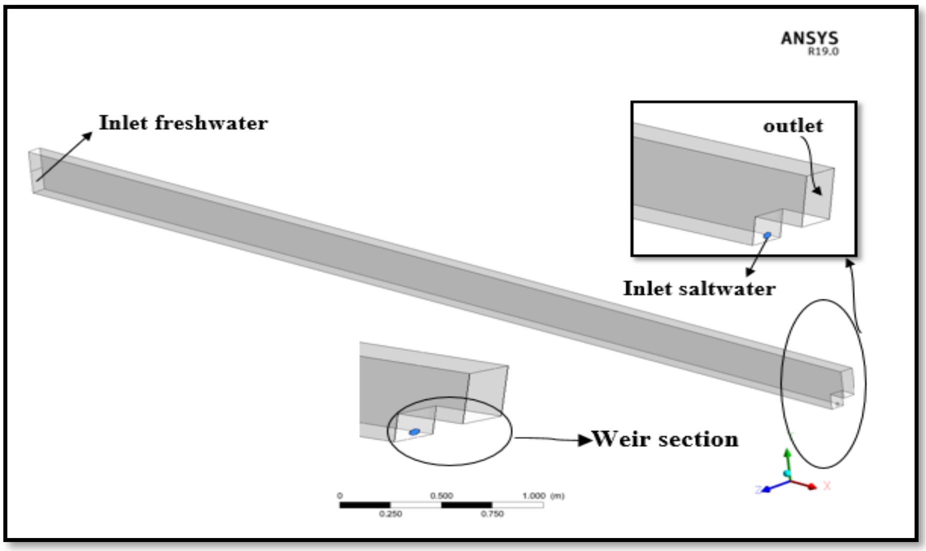


Figure 2. The geometry of the numerical model.

An irregular tetrahedral mesh was generated, and a variable mesh size of cell with the maximum of 0.01m, **Fig. 3**, and the mesh quality is subject to several criteria represented by skewness that were acceptable to good quality.

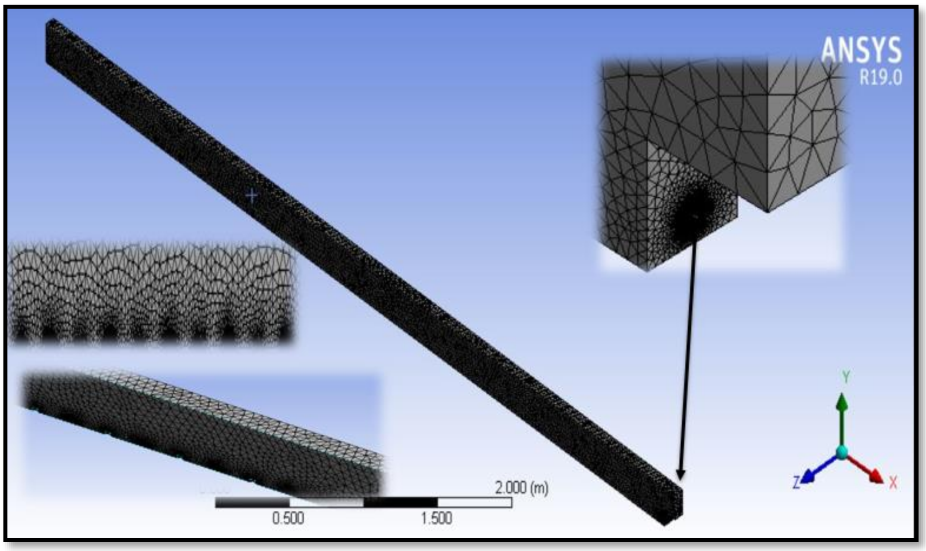


Figure 3. The meshing of geometry.

4. RESULTS AND DISCUSSION

All the conditions of the simulation runs were exactly as were set in the experimental laboratory work of (**Al-Fuady and Azzubaidi, 2021).** The numerical results of the simulated runs are compared with experimental results under the same conditions. The model results are presented using a contour of the volume fraction by comparing them with the wedge propagation distance and shape in laboratory experiments.

Generally, as the saltwater enters the flume from its downstream end of the flume, it moves toward the upstream direction of the flume. Due to density difference, saltwater wedge moves under the freshwater to a point where it is fully developed and is stationary. An interface mixing zone forms a thin layer between the fresh and saltwater. This layer is of high turbulence, and evident eddies are formed, as shown by **Fig. 4.**

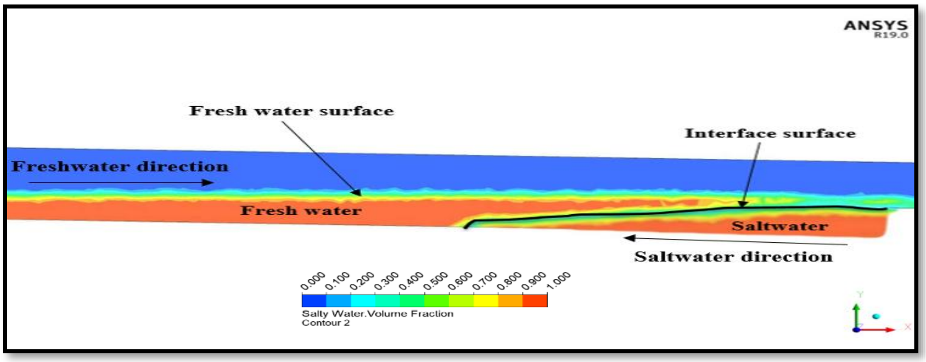
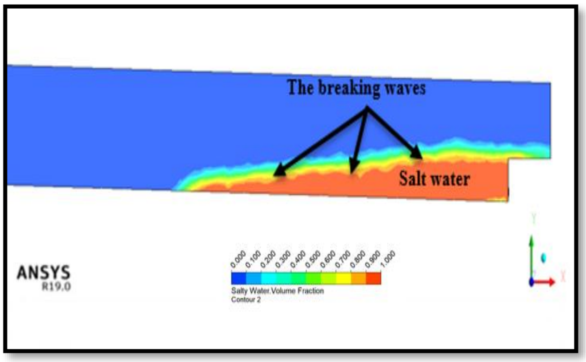
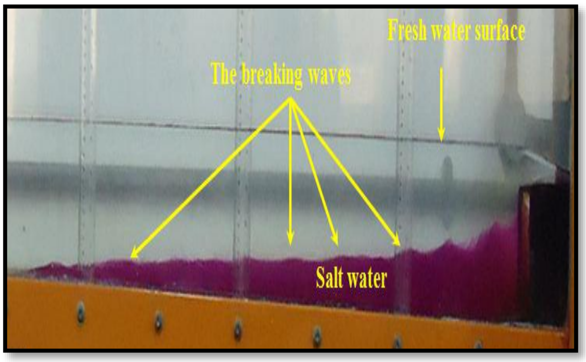


Figure 4. The interface between saltwater and freshwater.

Breakout waves are formed at the interface between salt water and fresh water exactly as in the laboratory experiment work documented by a snapshot as shown in **Fig. 5.** The generation of these waves may be referred to as the drag force generated between the fresh water and the saltwater.



a-CFD Model.

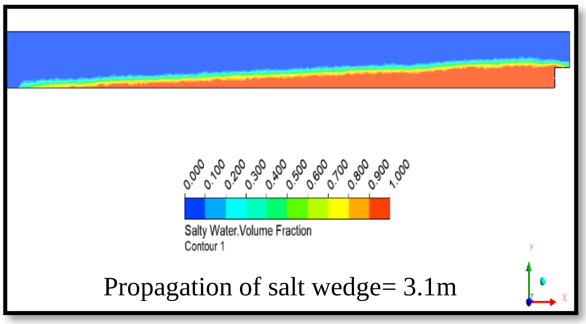


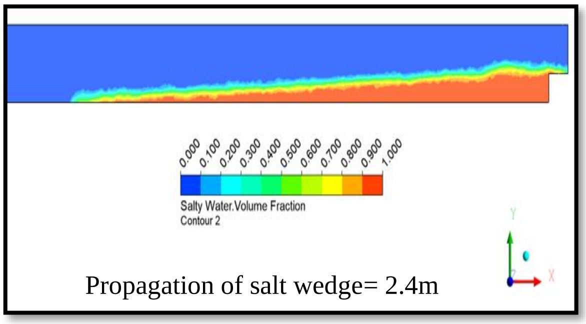
b- laboratory model, (**Al-Fuady and Azzubaidi, 2021**).

Figure 5. Breakout waves of the numerical and laboratory at the same conditions.

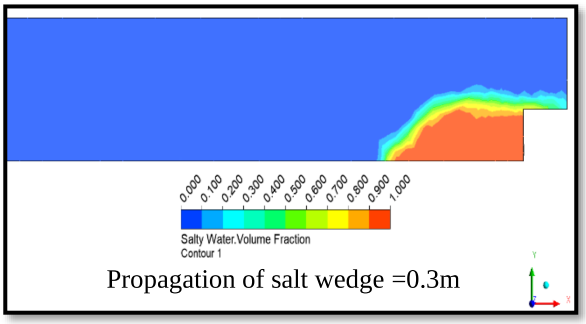
The propagation of the salt wedge depends on the discharge of freshwater, the roughness of the bed, bed slope of the flume, depth of saltwater, and the concentration of saltwater, which is in this study simulated by the densities of the saltwater. In the (**Al-Fuady and Azzubaidi, 2021)** study, the density of saltwater is one of the studied variables. In this study, the density is not included as a variable in the investigation and is considered constant. The experiment results of (**Al-Fuady and Azzubaidi, 2021)** with too close densities were selected with an average of 1023.4 kg/m^3. **Fig. 6 to Fig.9** show the propagation of salt wedge under different freshwater discharges and the slopes of the flume. **Table 2** shows the obtained propagation of salt wedge of twelve runs of both the laboratory experimental and the numerical models. Generally, the propagation of the salt wedge increases when the freshwater discharge was decreased under the same bed slope of the flume and when the bed slope of the flume was decreased under the same discharge of the freshwater. Maximum propagation of 3.1m is obtained at the lowest discharge value and the minimum slope of the flume. At slope, 0%, a reduction in the propagation of the salt wedge of 90.3% is achieved when the discharge is at its maximum value compared to that at minimum discharge. At the maximum slope of 3%, the propagation of the salt wedge is reduced to 74% compared to that of slope 0% at the minimum discharge.

The compassion between the results of the experimental study and the CFD model shows an excellent agreement. The relative average error for all runs is 2%, with a range of 0 to 16%. The maximum relative error of 16% was achieved when the slope of the flume bed is 0% and a root mean square error is 0.18.



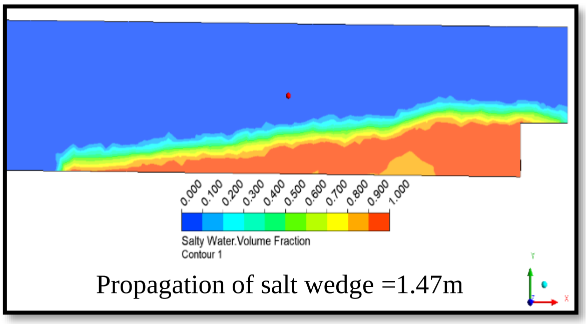


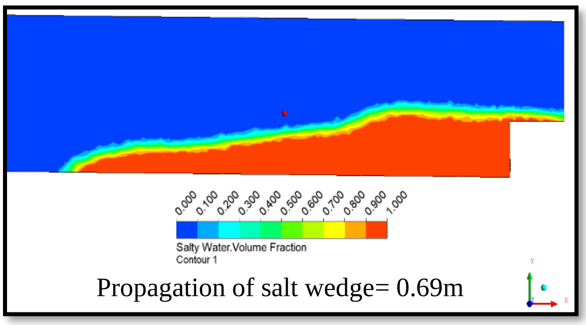
a- Discharge= 45.3 l/min. b- Discharge= 55.6 l/min.



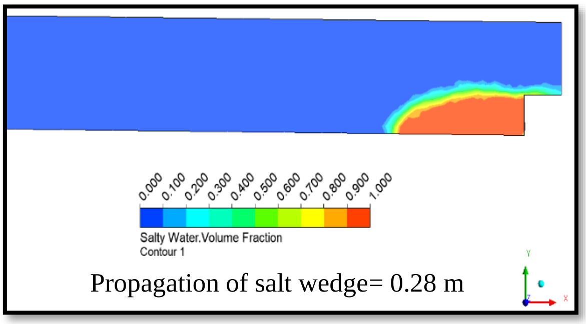
c- Discharge= 78.4 l/min

Figure 6. Propagation of salt wedge at different discharges and a slope of 0%.



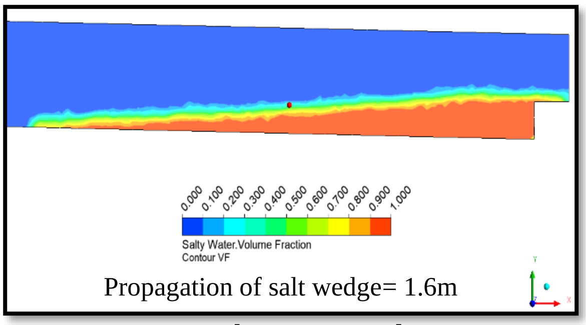


a- Discharge= 45.1 l/min b- Discharge= 61.3 l/min

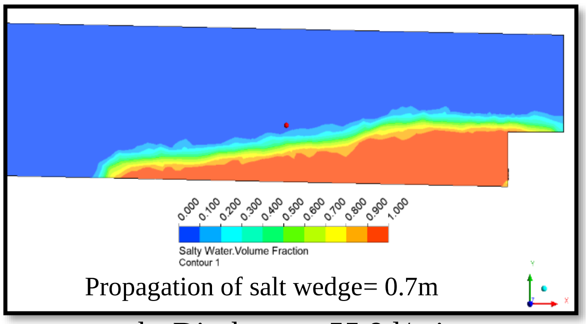


c-Discharge= 78.6 l/min

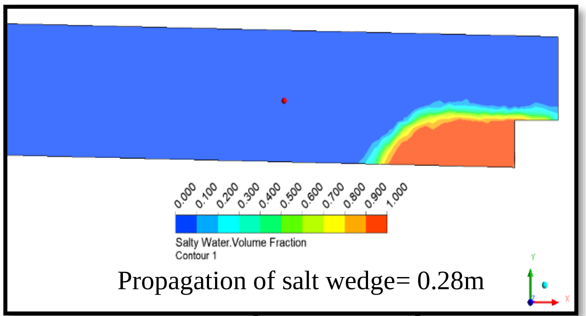
Figure 7. Propagation of salt wedge at different discharges and a slope of 1%..



a- Discharge= 17.4 l/min

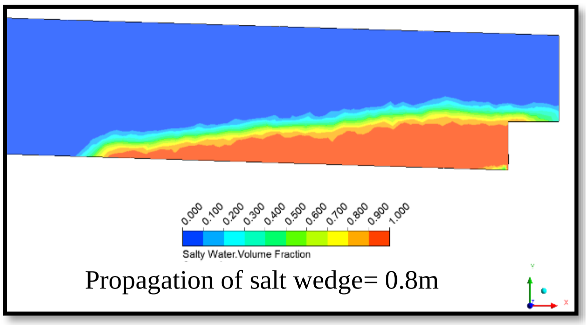


b- Discharge= 55.9 l/min

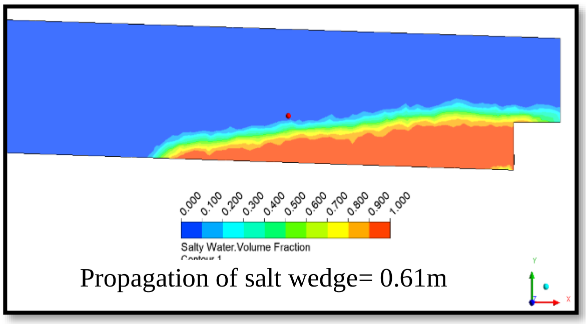


c- Discharge= 79.9 l/min

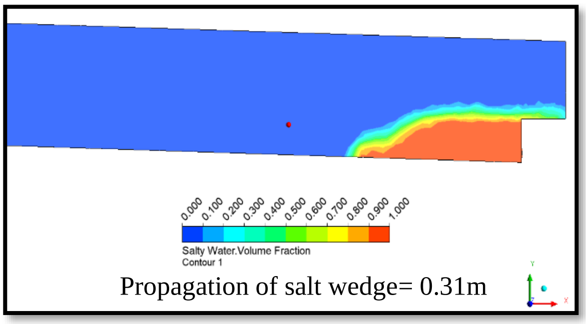
Figure 8. Propagation of salt wedge at different discharges and a slope of 2%.



a- Discharge= 45.9 l/min



b- Discharge= 54.6 l/min



c- Discharge= 72.6 l/min

Figure 9. Propagation of salt wedge at different discharges and a slope of 3%.

Table 2. The obtained propagation of salt wedge of both the laboratory experimental and the numerical models.

Slope	Discharge, *l/min*	Propagation, *m*		Relative error, %
		experimental model	CFD model	
0%	45.3	3.70	3.10	16%
	55.6	2.60	2.40	8%
	78.4	0.30	0.30	0%
1%	45.1	1.48	1.47	1%
	61.3	0.69	0.69	0%
	78.6	0.28	0.28	0%
2%	17.4	1.60	1.60	0%
	55.9	0.70	0.70	0%
	79.9	0.28	0.28	0%
3%	45.9	0.80	0.80	0%
	54.6	0.61	0.61	0%
	72.6	0.31	0.31	0%

5. CONCLUSIONS

According to the CFD model runs that were conducted by this study, the following conclusions were made:

1. the propagation of the salt wedge is inversely related to the applied freshwater discharge and the bed slope of the flume. The maximum propagation is obtained at the lowest discharge value and the minimum slope of the flume.
2. At the maximum slope of 3%, the propagation of the salt wedge is reduced to 74% compared to that of slope 0% at the minimum applied discharge. At the slope of 0%, a decrease in the propagation of the salt wedge by 90.3% is achieved when the discharge is at its maximum value compared to that at minimum discharge.

3. Based on the comparison between the results of both the experimental laboratory model and the CFD numerical model, the CFD software is quite valid for simulating the propagation of the salt wedge as the relative error is too small between the two models.

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