Using CFD Modeling to Simulate the Control of the Propagation of Salt Wedge using Inclined Roughness Elements

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Abstract. This research aims to simulate and use Computational Fluid Dynamics, CFD, to control the propagation of salt wedges. The flume has a cross-section of 25 cm in height and 7.5 cm in width with a length of 6 m and a zero slope. The simulated model is used to investigate the use of inclined roughness elements to control the propagation of salt wedges. The elements are blocks of 2 cm by 3 cm cross-sections having an inclined face in the direction of the flow, with a length of 2 and 3 cm. These elements were installed in two rows at both sides of the bed of the flume with variable spacing between them in the direction of the flow, and their centerline is inclined by an angle of 30 degrees in the direction of the flow. The simulation model was validated by comparing its output with a published laboratory experiment. Ten CFD model runs were conducted under two different discharges and five different spacing between the inclined roughness elements. The used discharges are 30 l/min and 45.3 l/min, and the spacing between elements was 3, 6, 9, 12, and 15 cm. The results demonstrated a good relationship between the obtained model runs and the observations of the laboratory experience under the same conditions. The result showed that when no roughness elements were used, the propagation of the salt wedge extended to 3.9 and 3.1 m at a discharge of 30 l/min and 45.31 l/min, respectively. The propagation of the salt wedge is reduced as the spacing increases to some limit and then starts to decrease when you use roughness elements. At the maximum applied discharge of 45.3 l/min, the propagation of the salt wedge was reduced by 82, 84, and 85% when the spacing between the blocks is 3, 6, and 9 cm, respectively. The percentage of reduction in the propagation of the salt wedge starts to reduce to 79% and 75% as the spacing between the blocks is increased to 12 and 15 cm, respectively. When the discharge is 30 l/min, the propagation of the salt wedge is reduced by 76, 74, and 78% at a spacing of 3, 6, and 9 cm, respectively. At the same time, the propagation is reduced by 58% at 12 cm and 53% as the spacing is increased to 12 and 15 cm.

Keywords: CFD; salt wedge; roughness elements.

1. INTRODUCTION

The propagation of salt wedges into rivers is a fascinating natural occurrence in various estuaries worldwide. The difference in densities between the salt water and the freshwater causes the salt water to migrate along the riverbed during the tide to a considerable distance upstream of the river mouth. Freshwater discharge, the roughness of the river and its longitudinal slope, the tide's maximum height, and the saltwater concentration are the main variables determining how long saltwater propagates upstream. The problem of this study states that the flow of salt water needs more studies and investigation to clearly understand and control the phenomenon of propagation of salt water. Many studies used various mathematical modeling to control the propagation of salt wedges, which studied a large turbulent channel flow eddy on one wall with transverse roughness features. The quality of water and soil significantly impacted the properties of porous media and water flow in the porous media and open channels [1-5]. Dritselis [6] investigated the viability of using a large eddy simulation to estimate turbulent channel flows with transversely positioned two-dimensional roughness features of square, circle, and triangle shapes on the bottom wall. The efficiency of multiple sub-grid-scale models was assessed using the results of simulations of turbulent flows in a channel using large eddy currents with two-dimensional Roughness elements of cross-sections that are square, circular, and triangular when characterized transversely positioned on the bottom wall of the channel [6]. Shamloo and Pirzadeh [7] investigated the effects of roughness density, flow submergence, and the turbulent flow characteristics of open channels was carried out. This investigation used an extended Werner–Wangle wall model to simulate a turbulent channel flow with rib elements on a bed as a large eddy. The results of the experiments were analyzed by comparing things like mean velocity, turbulence intensity, turbulent kinetic energy, and turbulent production profiles. Roughness density and flow depth increase with a pitch-to-height ratio at shallow depths. Together, they have a significant effect [7].

Briggs et al. [8] investigated the effects of roughness on flow and eddy formation in fractures modeled using numerical simulations. The lattice Boltzmann method was utilized in order to investigate how roughness influences flow in fractures (LBM). Dolomite fractures and statistically generated hypothetical fractures were modeled in the computer simulations that were run. When the fracture roughness was increased, the eddy volumes were increased, but the effective hydraulic conductivities were decreased, even though the Re values remained the same [8]. Servini et al. [9] investigated the impact of static and dynamic roughness elements on the flow separation process. They found that both types of roughness can have an effect. The researchers

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examined two distinct sizes and shapes of roughness elements. The first roughness element is relatively small and is located close to the point of vanishing skin friction, and the second roughness element is significantly larger and extends downstream [9]. Prasad et al. [5] conducted a study on the effect of river discharges controlled by a dam and tidal currents on the salt wedge intrusion in the Godavari River estuary on the east coast of India. The results show that the discharge of rivers during the rainy season and the tide currents during different seasons impacted the incursion of salts around the river mouth. Where turbulent mixing at the interface resulting from shear stress causes weak stratification and wedge length decline [10].

He et al. [11] conducted a study on the response of saltwater intrusion during runoff variability and sea level in the NANDU River Estuary, China. The hydraulics of salinity are simulated in a three-dimensional model using the finite-volume community ocean model. The results show that sea level and the high runoff variability impacted the saltwater incursion. The rate of surpassing salinity declines in the direction of the downstream river as runoff variability increases. Ospino et al. [12] studied saltwater intrusion dynamics in a Microtidal Estuary of the Magdalena River, Colombia. The impact of river flow rate, tide, and wind on mixing and saltwater intrusion in a three-dimensional numerical model is utilized to simulate the river estuary. The results show how winds and seasonal tides affect the spreading and mixing of salt water. It was discovered that variations in river discharges impact the length of the salt wedge. The water column is stable even under the impact of wind and tides at the most excellent release. The effect of wind force on tidal force is visible at medium discharges [12].

De Marchis et al. [13] studied simulations using large eddies to research should be done to determine how the irregular roughness shape affects the turbulent channel flows. Researchers investigated the mean flow in turbulent channel flows over irregular rough surfaces by running simulations with large eddies. According to the findings of the study of the mean velocity profiles, the outer region is where roughness crests have the greatest impact. In contrast, roughness cavities have the greatest effect in the inner region and a lesser effect in the outer region [13]. Yang et al. [14] conducted a laboratory investigation and analysis of the evolution of density and velocity profiles in an arrested salt wedge. The flume is supplied with fresh water from the upstream tank and saltwater from the downstream tank. The saline water was tinted red by adding Rhodamine WT dye, which was added sparingly. Flow velocity and density interface height were assessed based on the image and laser particle positioned down the flume. Analytically, the two-layer internal hydraulic theory is developed to solve the interface density height profile [14].

Zachopoulos et al. [15] studied by using the 3D numerical model to simulate the dynamics of the salt-wedge intrusion along the lower reach of the Strymon River Estuary, Greece. The constructed model demonstrated how the terrain of the area, the river flow rate, and the form of the bottom river all affect how quickly the salt wedge spreads. The results show that stratification could intensify when river flow is reduced. Additionally, placing submerged shallow sills on the river bottom at a specific distance can stop seawater from spreading across a much greater distance [15]. Cavalcante et al. [16] investigated an emergent and submerged semiarid alluvial open channel on sediment transport and roughness coefficients created by vegetation patches that are flexible. This study measured water and solid discharge directly using hydro sedimentometry and estimated the hydraulic roughness coefficients of Ipomoea pes-flexible caprate's vegetation element under emergent and submerged conditions using a simplified force balance model. Aquatic vegetation density affects flow transport capacity hydraulically, increasing vegetation resistance to the flow and decreasing sediment transport capacity [16].

Rao et al. [17] investigated the distribution of velocities experimentally and numerically within a compound meandering channel with double-layered and rigidly vegetated flood plains. Double-layered rigid vegetation was tested on meandering channel flow at relative depths of 0.34 and 0.45, which alternated emergent and submerged flow. Relative depth was 0.34 and 0.45. Numerical analysis used CFD codes. Alwan and Azzubaidi [18] conducted a series of numerical studies on the effects of large-scale geometric roughness in open channels of varying heights on the propagation of salt wedges. Utilizing large-scale geometric roughness in open channels is one way to alter the hydraulic behavior of the flow and achieve the desired results. The roughness of T-shaped elements was evaluated, each measuring 3 cm in height and arranged in either two lines, four lines, or fully rough configurations [18].

Shaheed and Azzubaidi [19] studied controlling salt wedge propagation by using the roughness element upstream of the river mouth. This study aims to numerically study the effect of using roughness elements in controlling the propagation of salt wedges upstream of the river mouth. The roughness elements work to increase the flow turbulence that dispersion the salt wedge that moves beneath the fresh water and reduces its propagation. Al-Fuady and Azzubaidi [20] conducted an experimental study on salt wedge propagation. The study aims to research the differentiation of profiles and propagation of salt wedges and the use of water and air curtains in controlling its propagation.

Furthermore, seventy-seven runs investigated the propagation of salt water. There were sixteen runs to control the salt wedge using water curtains and air. Moreover, it was discovered that water and air are effective ways of controlling the propagation of salt wedges. It is also notable that a minimum discharge of water curtains and air was obtained.

2. DESCRIPTION OF THE MODEL

The data of the flume system, Figure 1, which was simulated by a previously published study by [19], was used in this study. Flume-based system of 6m in length, 0.25 m in depth, and 0.075m in width. Fresh water is supplied at the upstream side of the flume. The downstream flume has an adjustable weir. With dimensions 0.1 m in length, 0.09 m in depth, and 0.075 m in width. This weir supplies salt water and discharges fresh water from the flume via an opening in the weir's center connected to a saltwater tank. In this paper, a new shape of roughness elements was investigated in controlling the propagation of salt wedges. The elements are blocks of 2 cm by 3 cm cross-sections having an inclined face in the direction of the flow, with a length of 2 and 3 cm, arranged in two lines with ten blocks. As shown in Figure 2, the roughness elements were placed in 0.25 m measured from the downstream end of the weir with 30°Inclination, the distance between each element is 3, 6, 9, 12, and 15 cm, as shown in Figure 3; the drawing was prepared by using SOLIDWORKS 2018 Software. Two discharges were applied, that is, 30 and 45.3 l/min.

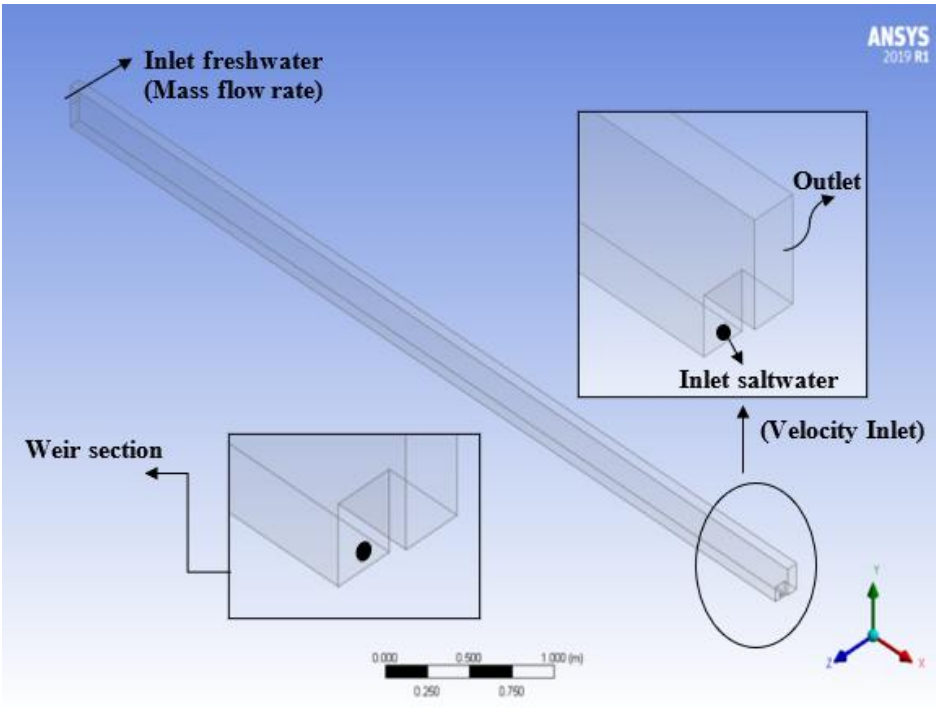

Figure 1: The geometry of the model of the flume system.

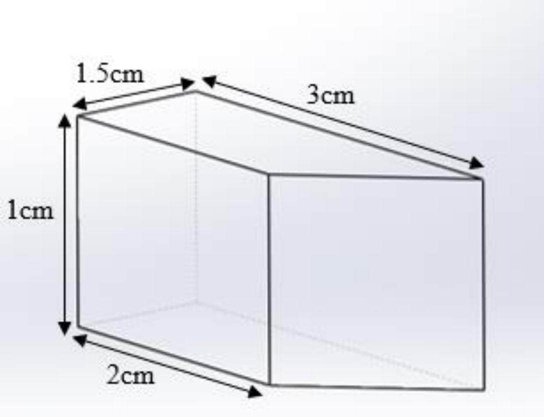

Figure 2: The Roughness Elements

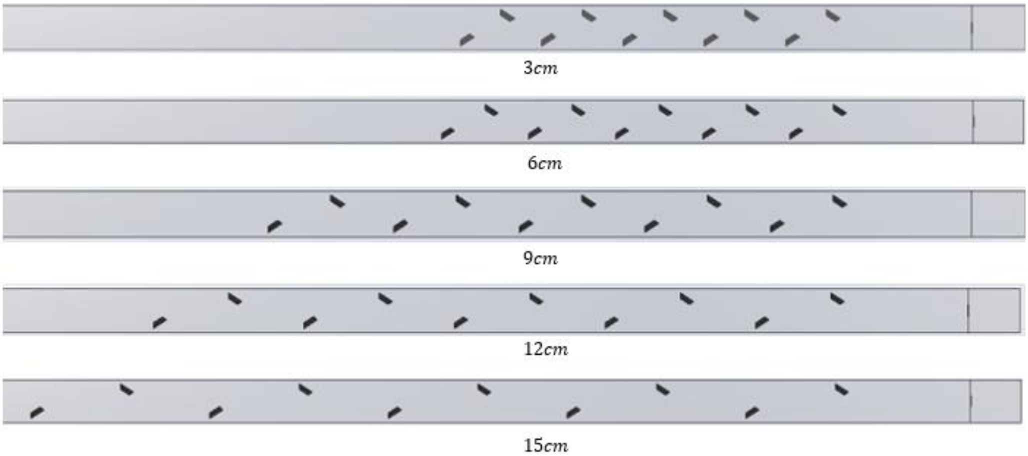

Figure 3: A top-view diagram showing the distribution of roughness elements.

2.1 Summary of the Runs by Using CFD Model

The commercial ANSYS FLUENT CFD is an efficient technique for simulating the hydrodynamic analysis of fluid flow under various conditions. The continuity and momentum equations derived from Newton's second law of fluid motion numerically used the Navier-Stokes solve equations and the ANSYS Fluent Software. The finite volume in the software solves the governing equations numerically. Open channels experience turbulent, incompressible flow. The turbulence model k-ε was employed in this study to simulate the flow turbulence away from the wall. The kinetic energy is K, and the dissipation rate [21]. It provides a valuable comparison of computational power requirements and accuracy. The inlet and outlet were defined as a pressure outlet and velocity inlet, and the flume's surface was free. The mass flow at the inlet and the pressure at the outlet were defined boundary conditions. The term "inlets" refers to the openings through which air and water flow into the domain. Surface tension between air and water is considered constant and equal to 0.072 N/m, air-salt water equals zero, and salt water and fresh water equals 0.00148 N/m [22]. The model is divided into tiny, atypical tetrahedral cells, as shown in Figure 4. Skewness is among numerous mesh quality parameters ranging from excellent to sound quality.

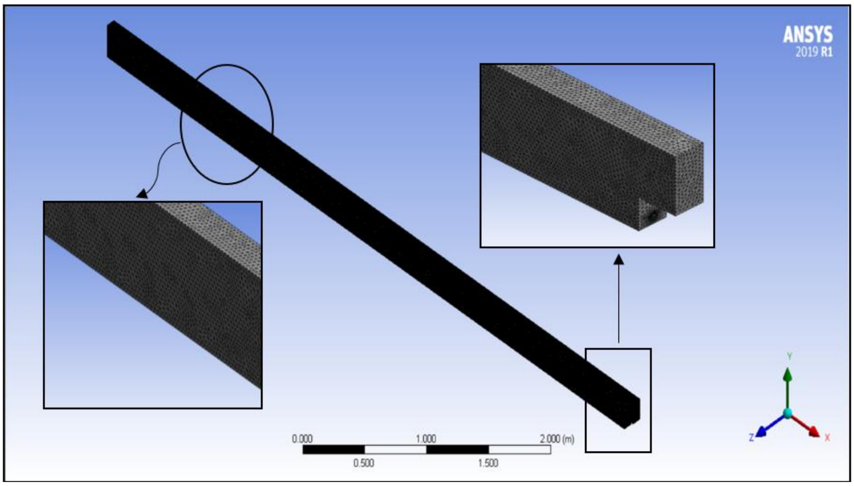

Figure 4: The meshing of the flume system.

The flow conditions and results of the two selected were the freshwater discharge of 30 l/min 45.3 l/min, the freshwater density of 998.2kg/m^3, and that for the saltwater of 1021.695 kg/m^3.

3. RESULTS AND ANALYSIS

The results were obtained without roughness elements. The flume's lowest discharge value produces the maximum propagation. The propagation of the salt wedge at 30 l/min was 3.9 m, as shown in Figure 5, while, at discharge at 45.3 l/min, the propagation of the salt wedge was 3.1 m. As shown in Figure 6, it is clear that when freshwater discharge is increased, the propagation is reduced. The propagation of slate wedge in case of applying 45.3 lm/min is less by 25% than that when that applied discharge is 30 l/min.

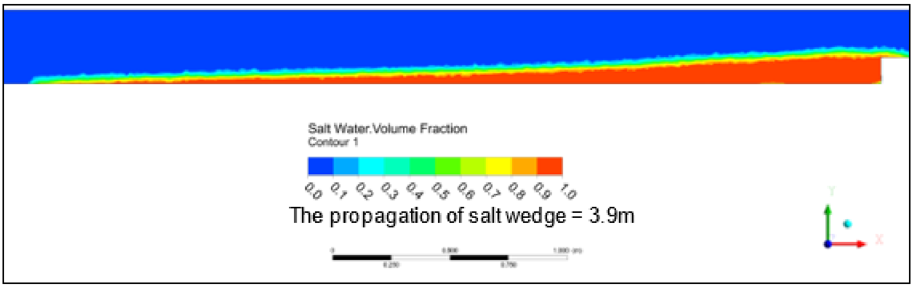

Figure 5: Propagation of salt wedge without roughness elements, applied discharge 30 l/min.

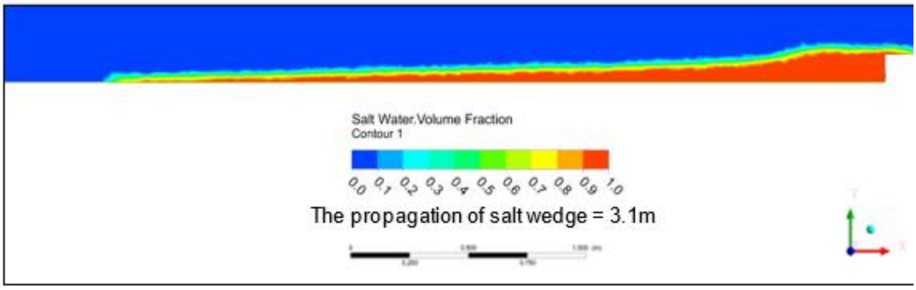

Figure 6: Propagation of salt wedge without roughness elements, applied discharge 45.3 l/min.

Figures 7 to 11 show the propagation of salt wedge with roughness elements at applied freshwater discharge is 30 l/min and constant roughness inclination of 30°, and different spacing between elements is 3, 6, 9, 12, and 15 cm. When the roughness element space is 3 cm, the propagation of the salt wedge is 1.3 m. The reduction in the propagation of the salt wedge is 76% compared to that without elements. While at 6cm, the propagation of the salt wedge is 1 m. It is a 74% reduction in the propagation of the wedge. The propagation of the salt wedge when the space is 9 cm is 0.85 m. It is a 78% reduction in the propagation of the salt wedge when compared to the run without using roughness elements. While the percentage also starts to reduce at 12 cm, the propagation of the salt wedge is 1.6 m. The reduction in the propagation of the salt wedge is 58% compared to that without elements. Finally, at 15 cm, the propagation of the salt wedge is 1.8m. It is a 53% reduction in the propagation of the salt wedge when compared to the run without using roughness elements.

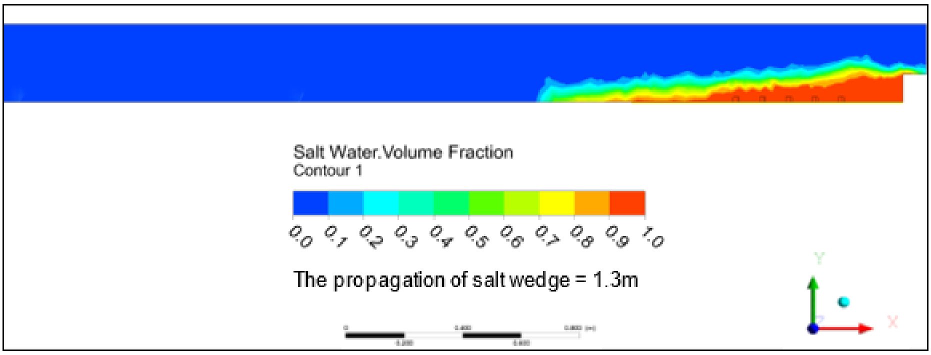

Figure 7: Propagation of salt wedge with roughness elements, applied discharge is 30 l/min, and spacing between blocks is 3 cm.

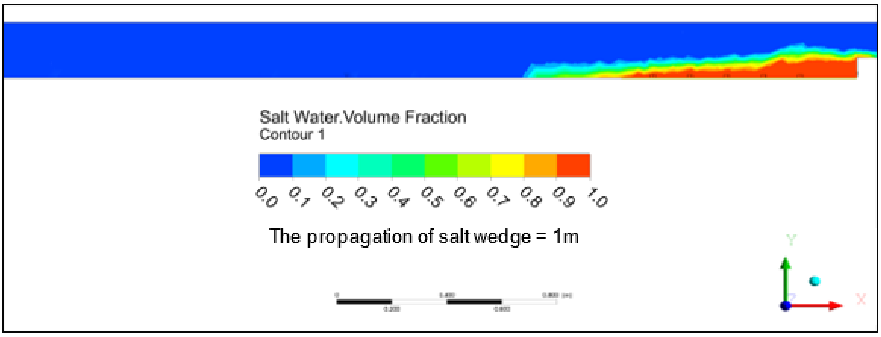

Figure 8: Propagation of salt wedge with roughness elements, applied discharge is 30 l/min, and spacing between blocks is 6 cm.

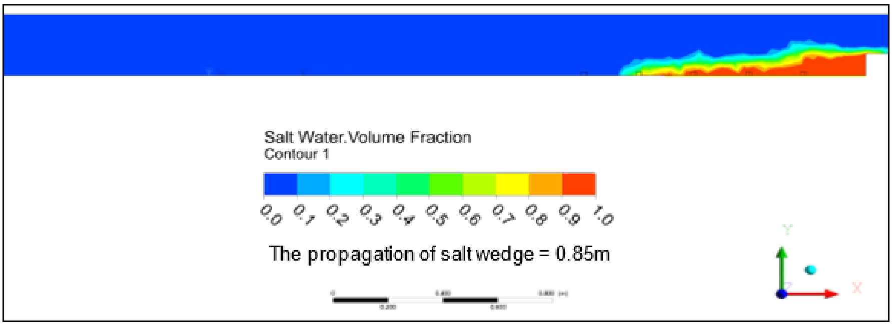

Figure 9: Propagation of salt wedge with roughness elements, applied discharge is 30 l/min, and spacing between blocks is 9 cm.

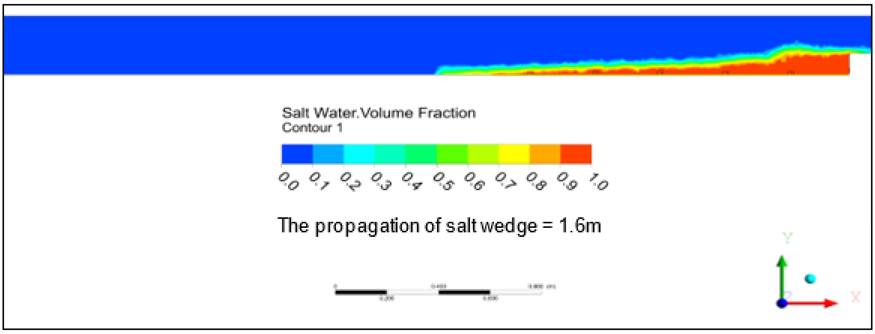

Figure 10: Propagation of salt wedge with roughness elements, applied discharge is 30 l/min, and spacing between blocks is 12 cm.

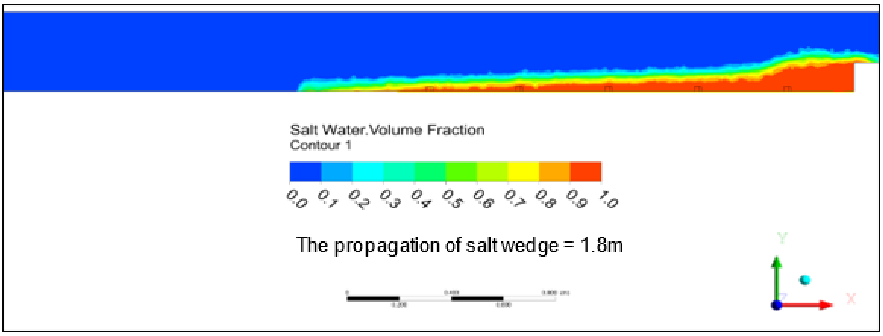

Figure 11: Propagation of salt wedge with roughness elements, applied discharge is 30 l/min, and spacing between blocks is 15 cm.

Figures 12 to 16 show the propagation of salt wedge with roughness elements at applied freshwater discharge is 45.3 l/min and constant roughness inclination of 30° and different spacing between elements (3, 6, 9, 12, and 15) cm. When the roughness element space is 3 cm, the propagation of the salt wedge is 055m. The reduction in the propagation of the salt wedge is 82% compared to that without elements. While at 6 cm, the propagation of the salt wedge is 0.5 m. It is an 84% reduction in the propagation of the wedge. The propagation of the salt wedge when the space is 9 cm is 0.48 m. It is an 85% reduction in the propagation of the salt wedge when compared to the run without using roughness elements. While the percentage also starts to reduce at 12 cm, the propagation of the salt wedge is 0.65 m. The reduction in the propagation of the salt wedge is 79% compared to that without elements. Finally, at 15 cm, the propagation of the salt wedge is 0.75 m. It is a 75% reduction in the propagation of the salt wedge when compared to the run without using roughness elements.

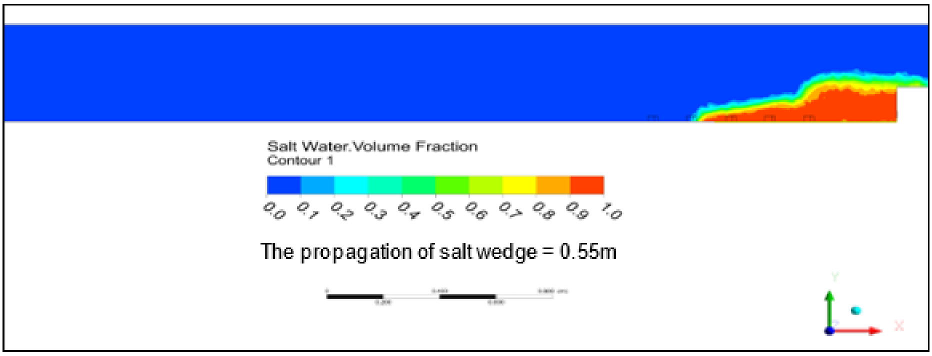

Figure 12: Propagation of salt wedge with roughness elements, applied discharge is 45.3 l/min, and spacing between blocks is 3 cm.

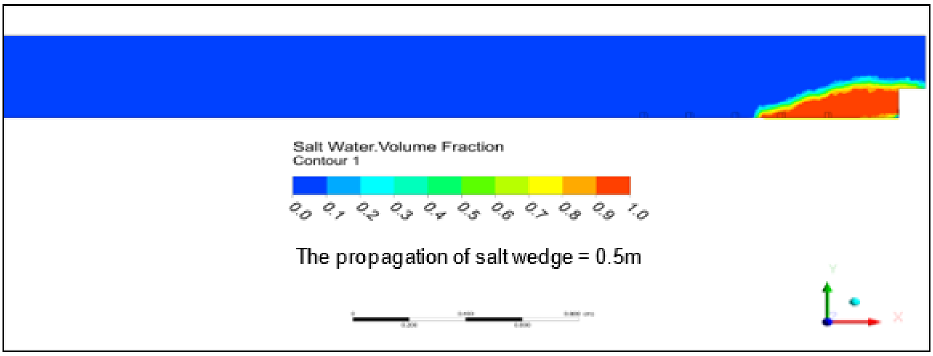

Figure 13: Propagation of salt wedge with roughness elements, applied discharge is 45.3 l/min, and spacing between blocks is 6 cm.

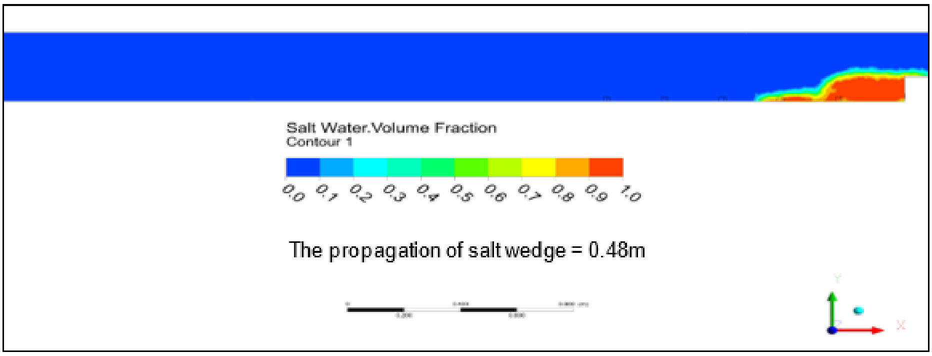

Figure 14: Propagation of salt wedge with roughness elements, applied discharge is 45.3 l/min, and spacing between blocks is 9 cm.

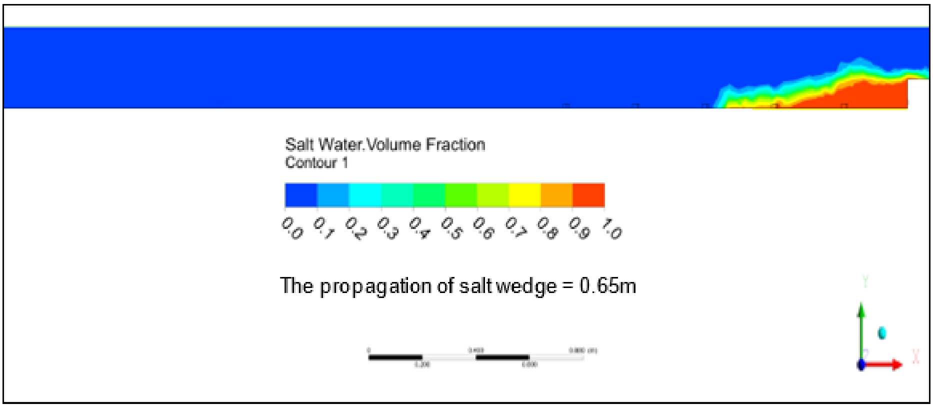

Figure 15: Propagation of salt wedge with roughness elements, applied discharge is 45.3 l/min, and spacing between blocks is 12 cm.

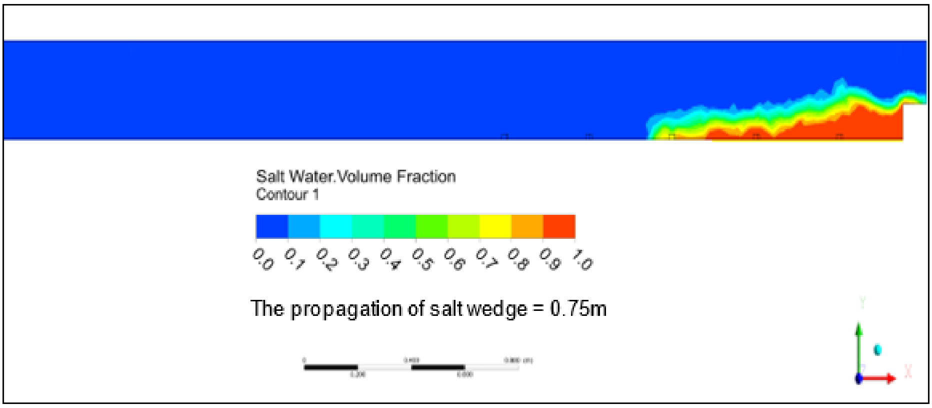

Figure 16: Propagation of salt wedge with roughness elements, applied discharge is 45.3 l/min, and spacing between blocks is 15 cm.

Table 1 summarizes all the obtained results of the conducted model runs. It is clear that the used roughness elements can significantly reduce the propagation of salt wedge and can be used to reduce its adverse effects as it propagates upstream the river mouth.

Table 1: The Propagation of Salt Water under different conditions.

Discharge l/min	**Spacing between blocks, cm**	**Propagation of salt wedge, m**		**Percentage of reduction in the propagation of salt wedge, %**
		Without roughness	**With roughness**	
30	3	3.9	1.3	76
	6	3.9	1	74
	9	3.9	0.85	78
	12	3.9	1.6	58
	15	3.9	1.8	53
45.3	3	3.1	0.55	82
	6	3.1	0.5	84
	9	3.1	0.48	85
	12	3.1	0.65	79
	15	3.1	0.75	75

4. CONCLUSION

The results of the CFD model runs carried out for this study led to the following conclusions:

- At the maximum applied discharge of 45.3 l/min, the propagation of the salt wedge was reduced by 82% at 3 m, 84% at 6 cm, and 85% at 9 cm. while the percentage started to reduce by 79% at 12 cm and 75% at 15 cm. When the discharge is 30 l/min, the propagation of the salt wedge reduces by 76% at 3cm, 74% at 6 cm, and 78% at 9 cm. While the percentage also starts to reduce by 58% at 12 cm and 53% at 15 cm.

- The results show that the propagation of the salt wedge is reduced as the spacing increases to some limit and then starts to increase.
- The roughness elements improve the flow turbulence that disperses and slows the salt wedge propagation beneath the fresh water.

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