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Salinity-Various Flow Characteristics Investigation in an Identical Meandering Channel

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ABSTRACT

Estuaries are one of the most productive ecosystems in the world, providing significant resources for humans and animals. However, the influence of various rainfall patterns due to climate change has affected the estuarine system, leading to changes such as salinity intrusion. This study aims to verify how river discharge changes affect salinity mixing within a meandering channel and the effect of flow patterns due to curvature. An experimental hydraulic investigation was conducted at Universiti Teknologi Malaysia (UTM) Johor Bahru. The cross-sectional profiles along the meandering channel are discussed in this paper. The findings prevailed as a typical characteristic of the salt-wedge estuary and indicated the process of estuarine mixing. As the saltwater flow upstream, the salinity level drops due to the dilution process. Additionally, the greater density of seawater compared to freshwater causes it to remain in the lower layers of the water column. The flow pattern in curvature is influenced by the velocity of the inner and outer banks, where velocity has been seen to be higher at the outer bank, allowing the salinity to flow quickly near the inner bank. The present study will be useful in predicting the estuarine salinity response to river inflow.

1. Introduction

Salinity intrusion in estuaries is a topic of interest to many researchers studying water resources. Various techniques have been employed to describe and analyze the salinity distribution in estuaries. Note that the interaction of salinity patterns in estuaries results from the interplay between estuarine thermology and topography, tidal elevation at the estuary mouth, and variation in saline water between the ocean and freshwater discharge [1]. Therefore, these factor interactions determine the estuarine mixing mechanisms and the saline water movement process. Understanding the link between estuarine conditions is the key to developing the assessments of the predominant factor affecting salinity mixing.

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Consequently, the maximum distance of seawater from downstream depends on the freshwater discharge output. Since this discharge fluctuates daily, seasonally, and even annually, seawater may arrive in the upstream catchment at various locations and times. The consistency, functionality, and sustainability of estuarine habitats are influenced by the quality, quantity, and timing of freshwater inflow (as well as variations in salinity, nutrients, and sediments) [2]. Moreover, there are a growing number of studies in salinity mixing, including theoretical analysis [3], field data analysis [4-6], numerical simulation [7-9] and physical modeling [10-13]. Within this context, the study aims to improve understanding of the complex process in the estuarine system, including various forcing mechanisms of saltwater intrusion due to mixing freshwater and saltwater. Estuaries are typically characterized by a salinity gradient from seawater downstream to freshwater upstream. Note that the mixing of these two water masses is influenced by various factors, including river discharge, tides, wind, and estuary topography, and the associated physical mechanisms are very complex [14].

As documented by many laboratory studies, the research method using a physical model for flume testing salinity mixing is mainly for straight channels. Although meander is the most common planform acquired by the natural river, the meandering channel is less applied in the study. This is because the channel flow is considerably more complex due to the interaction mechanism as well as sinuosity compared to a straight channel [15, 16]. Apart from that, recent experimental research on salinity mixing in meandering river was flume test studies by Jumain *et al.,* [17] providing an important reference for observational techniques and data processing.

According to the above reason, the present study aims to investigate, in a general sense, the relationship between the changing discharge of freshwater and salinity mixing through a meandering channel. Subsequently, we study the effect of curvature on flow characteristics. For this purpose, several experimental runs have been conducted at different freshwater flow rates: low, moderate, and high. All these experiments were conducted over a non-mobile bed with a smooth rigid wall. Besides that, a rigid boundary channel is more appropriate for studying the fundamentals of flow interaction and flow characteristics than opting for a movable bed. The salinity mixing pattern and the effect on the cross-sectional area in the meandering channel will be discussed in detail in a subsequent report.

2. Methodology

2.1 Experimental Setup

The experimental work employed a meandering channel in the Hydraulic Laboratory, School of Civil Engineering, UTM Johor Bahru. A 10-meter-long channel with a rectangular cross-section, 0.3 meters wide and 0.6 meters deep, was constructed of transparent acrylic with a fixed smooth wall Figure 1. Here, the channel was made with a rigid boundary type of cross-section. The flume scale was 1:20, with a bed slope of 0.125 %. Moreover, the channel bed was filled with a uniformly graded sand layer (d_{50} = 0.8 mm) and lined with cement to form a non-mobile bed channel. The channel planform comprised three identical meander wavelengths with a sinuosity of 1.09 or a deflection angle of 25°.

Fresh water was supplied from a sump with a maximum capacity of 15 liters per second (L/s). Note that fresh water runs from one end of the tank, overflowing at an adjustable tailgate at the other end. The mixed saltwater tank was connected to a submersible pump, with a valve regulating the discharge. Consequently, the flow initially enters the flume as a typical gravity current. The red dye tracer demonstrates saltwater to visualize the mixing process at a salinity level of 15 parts per thousand (ppt).

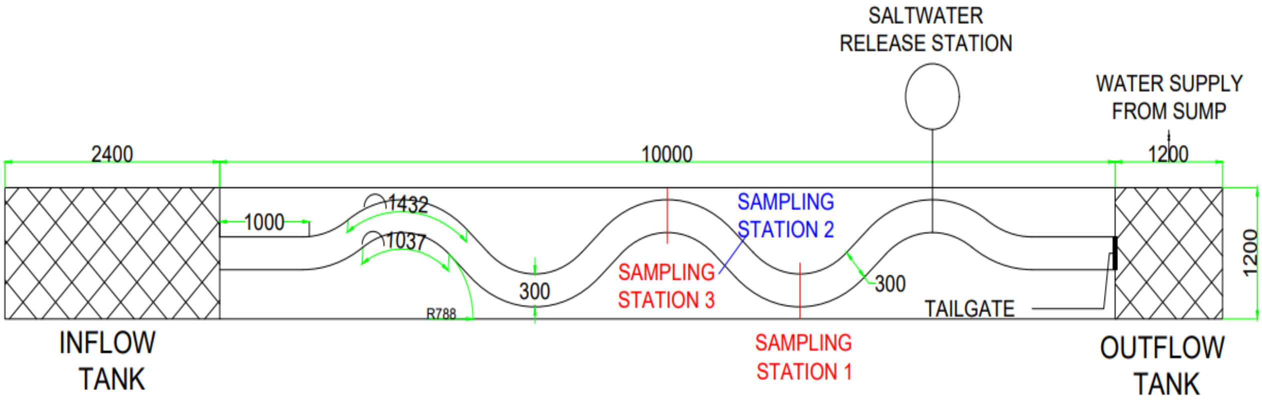


Fig. 1. Diagram of the meandering channel layout

The flow discharge of freshwater was measured by a Micronics Portaflow PF330 Ultrasonic Flow Meter. Here, the transducers were mounted to the 80 mm pipe to allow the flow measurement. At the downstream end of the channel, a manually controlled tailgate was constructed to control and maintain the desired depth of flow in the flume. The water surface measurement was performed with the assistance of a digital point gauge, operated manually at the center of the cross-over section. All the measurement was conducted under uniform flow conditions by setting the water surface elevation through the downstream tailgate parallel to the valley bed slope at each meander wavelength.

Water samples were collected using a self-made siphoning device, as illustrated in Figure 2. The instrument was placed at three stations with a longitudinal distance of half wavelength, namely Section 1, Section 2, and Section 3, as depicted in Figure 3. The position of the measurement section, Section 1, was set at 1.48 m from the saltwater discharge since it is impossible to measure the salinity accurately close to the flow discharge. With regards to the flow pattern characterization, measurement in Section 2, which is a straight channel, was included and measured. Subsequently, Section 3 covers the maximum upstream movement of salinity. Meanwhile, Figure 4 exhibited the cross-section of the water sample location for each station along the meandering channel with different freshwater discharge and water depths. With the assistance of a YSI 30 SCT salinometer, the salt level at each station was monitored for 120 seconds. Table 1 presents the locations of the sample stations. Here, three series of runs were carried out, characterized by different freshwater discharge and constant saltwater discharge. Salinity patterns were analyzed and visualized through plotted isohalines using Tecplot 360.

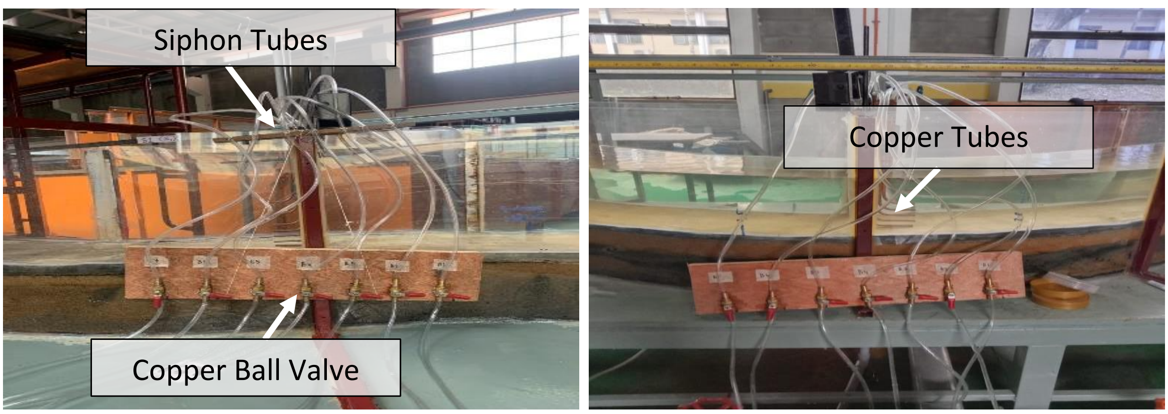


Fig. 2. A self-made siphoning device in a meandering channel

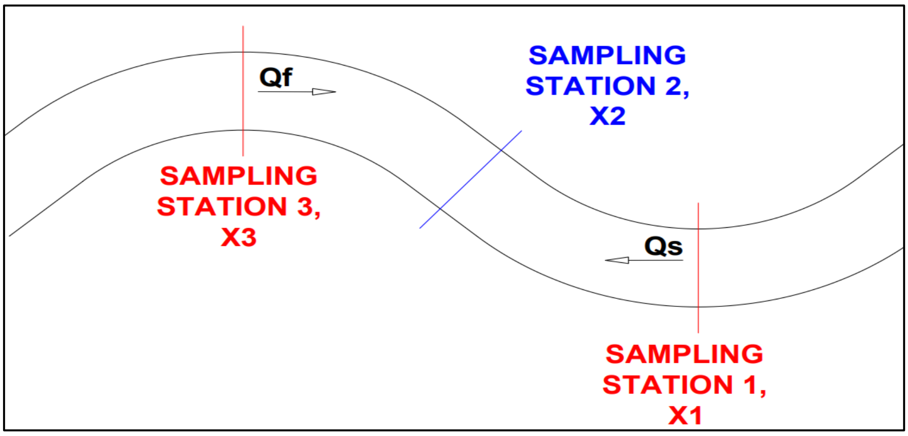


Fig. 3. Data measurement section

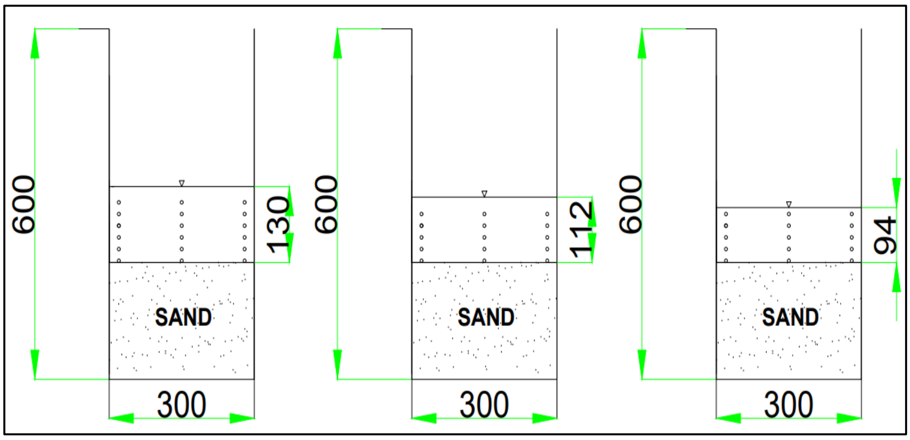


Fig. 4. Cross-section of water sampling points for each station along the meandering channel with different freshwater discharge and water depth

Table 1
Location of sampling stations

Station	Distance from movable tailgate, x (cm)	x/L
1	352	0.35
2	426	0.43
3	500	0.50

3. Results

The most significant features studied in this experiment are the cross-sectional area, width, and depth of the salinity mixing pattern driven by freshwater discharge and the curvature in a meandering channel. Table 2 presents the experimental condition for each series of runs. Q_f, Q_s, H, and S_o represents freshwater discharge, saltwater discharge, water depth, and initial salinity value.

Table 2
Summary of experimental condition for each series of runs

Case	Condition	Q_f (L/s)	Q_s (L/s)	H (cm)	S_O (ppt)
1	Low	2.4	4.2	9.4	15
2	Moderate	3.2	4.2	11.2	15
3	High	4.8	4.2	13.0	15

3.1 The Relationship between the Variation in Freshwater Discharge and Salinity Levels in a Meandering Channel and the Influence of Curvature on Flow Characteristics

Figures 5 to 7 depict the observed cross-sectional salinity profiles varying levels of low, moderate, and high freshwater discharge for each station, Section 1(a), Section 2(b), and Section 3(c), considering different relative depths using the *z/D* ratio (*z* is the depth measured from channel bed and *D* is the total depth flow). Note that the legend represents the salinity level in the channel, with red indicating the highest salinity and blue indicating the lowest salinity. Salinity levels (S) were analyzed as the relative salinity S/S_o where S_o represents the initial salinity value.

It is evident that when the river discharge is significantly low, salt intrusion can extend further upstream. Conversely, when the river discharge is relatively high, the salt intrusion lies only at the mouth. These findings are reasonable because the lower tide (neap) can be readily swept away by the ambient freshwater flow during the rainy season when the estuary is in a discharge-dominated condition. On the other hand, the estuary is tidal dominated during the dry season, and the higher tide (spring) could move farther inland with no difficulty (low freshwater flow). In other ways, rainfall can indirectly influence the increase of tide in estuaries by affecting river discharge. When there is heavy rainfall, the amount of freshwater flowing into an estuary from the river will increase, which can cause a decrease in salinity and a shallowing of the saltwater wedge.

The measured salinity profile at various relative depths reveals that the salinity is highest at the bottom of the channel and diminishes towards the surface due to variations in density. The dilution process still occurs in the middle of the channel depth, but the salinity level approaches zero at the water surface. Hence, salinity typically creates a stratification (variation in density) along the channel. It is demonstrated clearly that penetration and mixing occur at the bottom channel. The lighter, less dense freshwater rests on top of the denser saltwater in the upper layer, flowing downstream toward the ocean. Meanwhile, the heavier saltwater is typically found in the lower layer, extending upstream beneath the lighter freshwater, forming the salt wedge [18]. These phenomena represent a salt wedge formation in the channel, which will continuously intrude upstream until the pressure equalizes, as supported by Aziz *et al.,* [19] and Nuryazmeen *et al.,* [20].

Note that the salinity stratification in estuaries can be affected by the curvature. The increased velocity caused by saltwater flow moving from bend apex to cross-over caused significant shift events at the salt/freshwater interface. As observed in Sections 1 and 3 (bend apex), the salinity profile shifts towards the channel's inner bank and moves back towards the center as it becomes straighter at Section 2 (cross-over). The isohalines also reveal that the salinity profiles rise with the curvature channel near the inner bank. This behaviour results from the lower velocity at the inner bank than at the outer bank. Furthermore, previous studies by Ferguson *et at.,* [21] and Kasvi *et al.,* [22] reported similar results where higher velocities and erosion occur near the outer bank beyond the bend apex. This results in the saltwater flowing faster at the curvature's inner bank than the outer bank due to lower velocities.

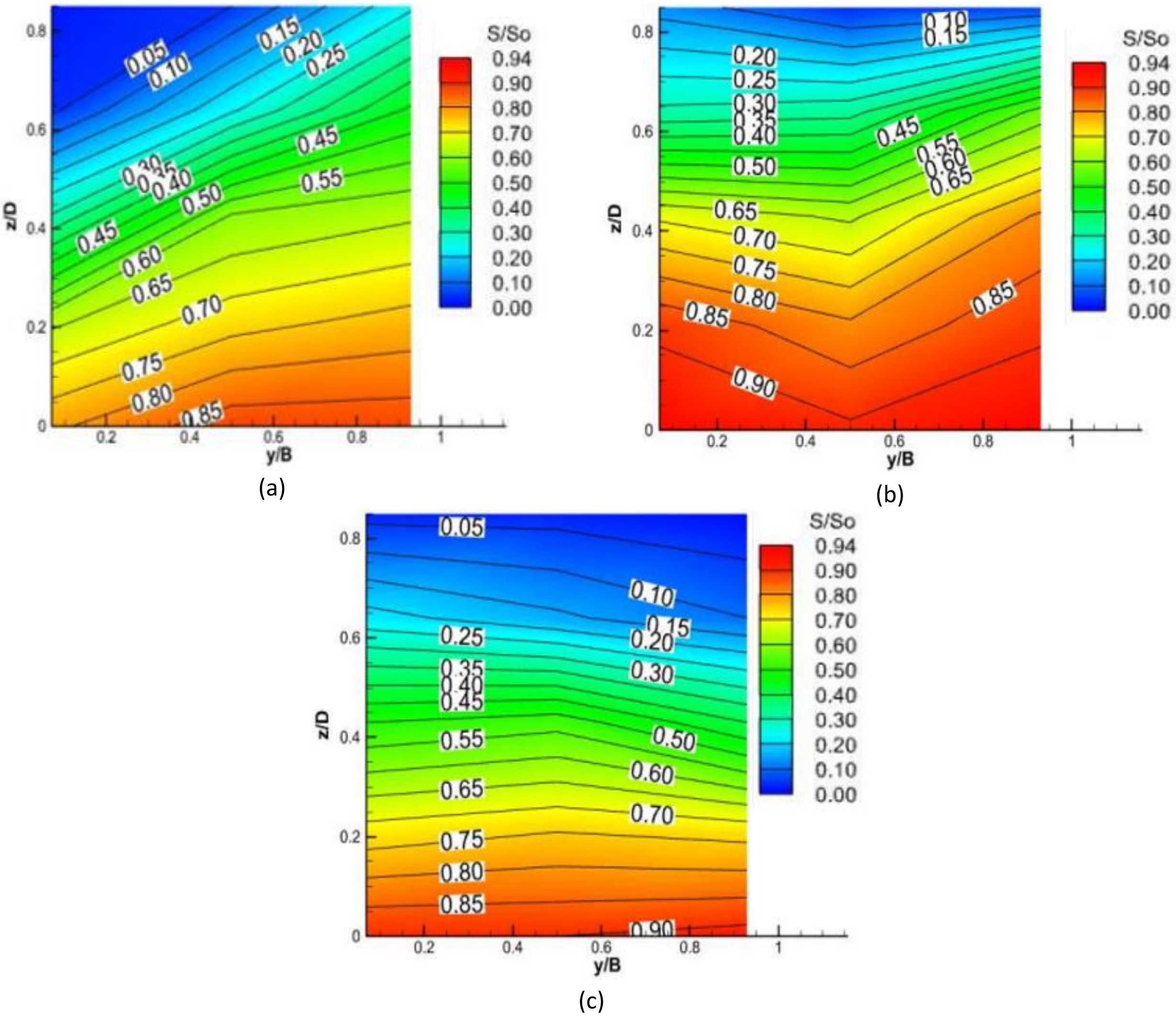
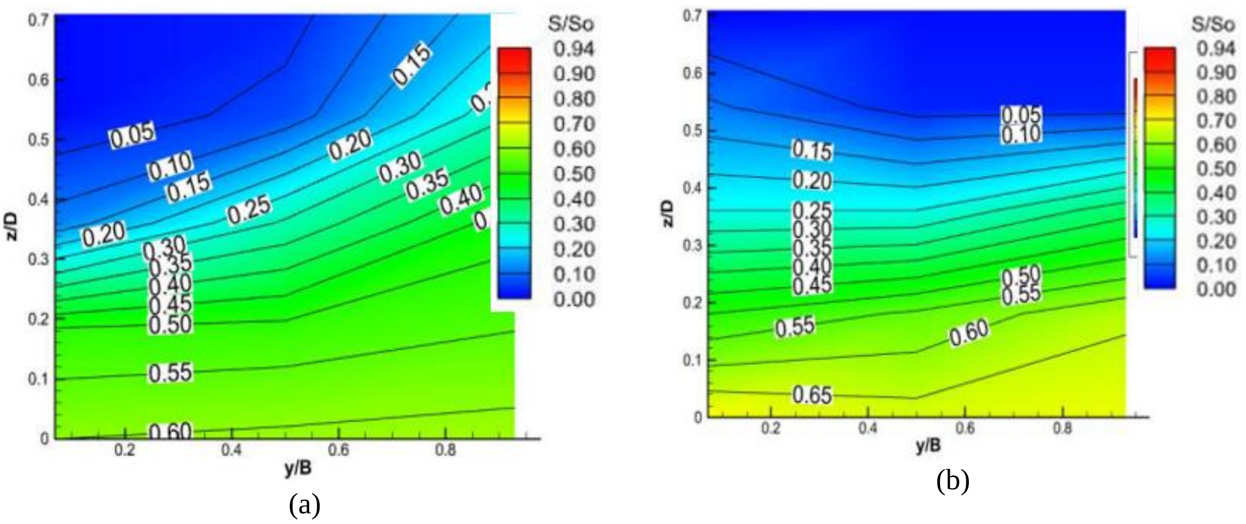
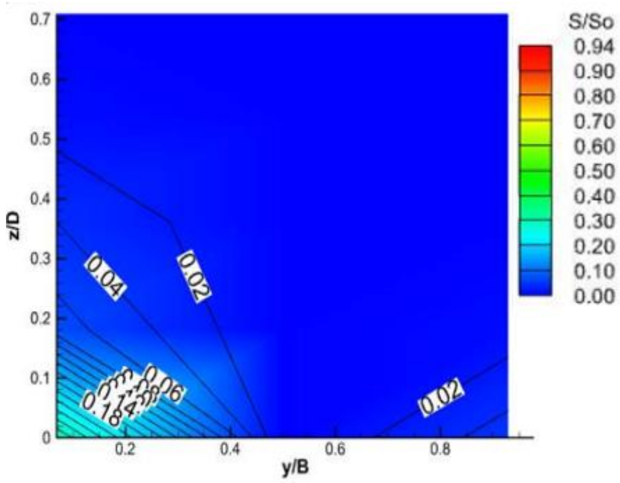


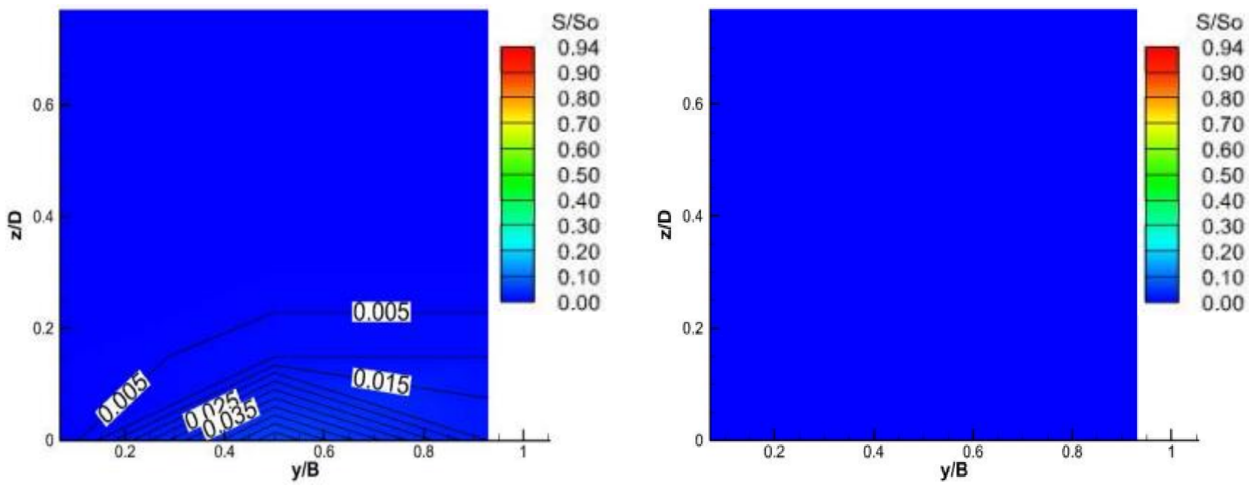
Fig. 5. Salinity profile of Section 1 (a) at bend apex, Section 2 (b) at cross-over and Section 3 (c) at bend apex. The contour represents the isohaline of water intrusion at Case 1 Q_f = 2.4 L/s





(c)

Fig. 6. Salinity profile of Section 1 (a) at bend apex, Section 2 (b) at cross-over and Section 3 (c) at bend apex. The contour represents the isohaline of water intrusion at Case 2 (Q_f = 3.2 L/s)



(a) (b)

Fig. 7. Salinity profile of Section 1 (a) at bend apex and Section 2 (b) at cross-over. The contour represents the isohaline of water intrusion at Case 2 (Q_f = 4.8 L/s)

4. Conclusions

This paper attempts to enhance the understanding of salinity mixing and flow characteristics in a meandering channel under various assumptions for river discharge. The cross-sectional patterns of saline-fresh water mixing under different depths at different sections was also considered. Therefore, the following conclusions that can be drawn from the findings:

i. River discharge significantly affects the patterns and the mixing process between salt water and fresh water. An increase in freshwater discharge leads to flushing, where the ambient freshwater flow washes away the saltwater.
ii. Stratification flows that occur in the channel are evident. The salinity profiles demonstrate that the bottom has higher salinity than the water surface. It suggests a typical salt wedge estuary. As the saltwater current flows upstream, mixing and dilution take place. Note that salinity is the highest downstream (near the sea) and progressively decreases upstream (river flow).

iii. The pattern of salinity is influenced by channel curvature. A high density of salt water tends to shift toward the inner bank of the meandering channel where velocity is decreasing. Meanwhile, at the cross-over section, the salinity flow shifts towards the center of the flume channel.

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