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Idealised Estuary Salinity-Morphology Effect Characterisation Investigation

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ABSTRACT

Estuaries are bodies of water along the coasts that are formed when fresh water from rivers flows into and mixes with salt water from the ocean. The density of seawater is greater than fresh water and it varies with salinity and temperature. Fresh water tends to float on top of seawater because of its lower density. Human-induced activities like the dredging of shipping lanes along the bottom estuarine, the dumping of industrial wastes into the water system, and shoreline development influence estuarine dynamics which include the mixing process. These activities lead to salinity changes and further adversely affect the estuarine ecosystem. The purpose of this research is to verify how salinity-morphology relations change in an estuarine system under various rainfall patterns, more specifically under extremely high rainfall conditions. The experiment that has been conducted studied the salinity-morphology relationships for a variety of rainfall patterns, most particularly for exceptionally high rainfall conditions, using an idealised channel. In the first part of this research, the morphology changes of the mixing between salt water (estuary) and freshwater (river) for different rainfall patterns, had been investigated in laboratory experiments. Fresh water was released from one end of the flume channel and overflowing over the weir at the other end. Meanwhile, salt water was represented by the red dye tracer released slowly through a weir and intruded horizontally to the upstream as a gravity current. In this experiment, an artificial roughened bed section was used as morphology change. The salinity pattern is plotted using Microsoft Excel. The salinity levels were measured at selected stations along the channel/longitudinal (*x*-axis), and also in transverse (*y*-axis) and vertical directions (*z*-axis) within the time duration. The observed salinity profile showed the difference in salinity level between heavy and light rain conditions with morphology effect where during heavy rain, the salinity level will decrease, hence, the existence of an artificial roughened bed section will affect the time taken for the process of mixing between salt water and fresh water.

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1. Introduction

An estuary is a term that refers to a place where freshwater (river) meets salt water (ocean) [1-3]. However, there are various estuarine definitions depending on the viewpoints of other groups or parties. Sea and river characteristics coexist together in estuaries, making them an extremely versatile ecological type. Besides that, an estuary is a complex ecological system that represents the difference between freshwater and coastal waters [4-7]. Based on mixing characteristics, estuaries can be classified as vertically mixed, slightly stratified, strongly stratified, or saline-wedged. The mixing that occurred in an estuary is crucial for the sediment, nutrient, and pollution distribution in a coastal area [8-12]. Fresh water from the river was less dense than salt water, therefore it was more likely to float on top of the salt water because of its lighter weight. If the estuary is sufficiently deep, salt water from the sea can pass through it, but fresh water running downstream will remain above the saltwater layer and end up in the ocean. This type of estuary was known as a salt-wedge. When mixing occurs, the estuary's salinity distribution progressively changes in space and time. Tidal influences, streamflow, differences in water density, estuarine features, wind effect, and Coriolis effect all have a role in salinity changes [13-21].

While fresh and saltwater meet, the water cycle is affected, and the mixing process caused by density differences between the two water masses will take place in estuaries [22,23]. The density of seawater can be affected by the salinity and temperature of the water. There is a wide variety of salinity and temperature in an estuary. When this happens, it has a significant impact on density because temperatures only have a minor impact on density. In environmental engineering, mixing in a shallow flow, such as that seen in estuaries and rivers, is a critical issue. The wind-driven transfer of suspended mining products into ponds, for example, can cause pollution spread, sediment movement in rivers and coastal waterways, algal blooms, and pond algal blooms. These procedures directly affect water quality and can have a significant impact on the ecosystem.

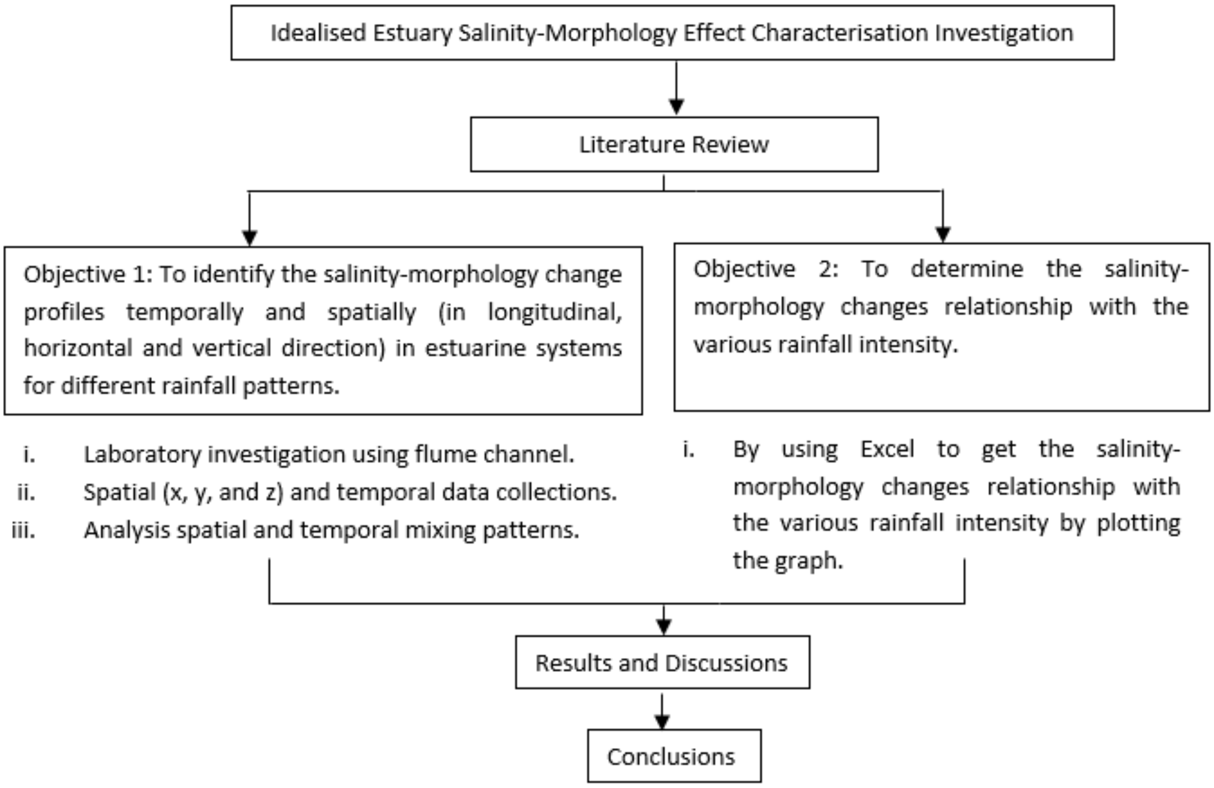
In addition, salinity intrusion into estuaries, in general, is mostly affected by river discharge and tidal levels. Other than that, wave height and river mouth shape are two further external factors that might affect salinity changes. Arise has been the subject of intense investigations during the past decades. However, there have been very few salinity-morphology changes investigated in idealised estuarine systems, specifically for different rainfall patterns. Salinity-morphology changes distribution and the length of estuaries could be considered the most important environmental factors impacting the existence and dispersion of organisms in estuaries. Hence, for this research purpose, a laboratory investigation is carried out to investigate by developing salinity-morphology models for different rainfall patterns using an idealised channel.

In a nutshell, it is important to conduct studies in estuaries because they provide ecosystems for a diverse range of flora and fauna. In addition, they act as filtration systems for terrestrial contaminants and flood defences [24-26]. The estuary's dynamics, including the mixing between saline water and fresh water, are affected by numerous human activities along its shoreline, such as dredging and coastal development [27-29]. The dredging operation may lead to salinity changes, which might further impact the estuary habitat. Salinity patterns may also be affected by constructions in the estuary or along the riverbank.

2. Methodology

A laboratory investigation was conducted in a flume to observe the mixing in a salt-wedge estuary. An overflow weir is built at one end of the canal, with salt water entering the weir bottom and flowing upstream as a gravity current. In the straight channel, mixing will take place on the *x*-

axis, *z*-axis, and *y*-axis directions simultaneously. By applying red dye tracers, the mixing patterns of saltwater intrusion have been examined in terms of their spatial and temporal distribution. The spatial and temporal salinity profiles in the flume channel are also studied through plotted graphs to gain a good understanding. The results show that salinity differences occurred due to the interfacial mixing between salt water and fresh water. Briefly, the study methodology chart is reflected in Figure 1.



Objective 1: To identify the salinity-morphology change profiles temporally and spatially (in longitudinal, horizontal and vertical direction) in estuarine systems for different rainfall patterns.

i. Laboratory investigation using flume channel.
ii. Spatial (x, y, and z) and temporal data collections.
iii. Analysis spatial and temporal mixing patterns.

Objective 2: To determine the salinity-morphology changes relationship with the various rainfall intensity.

i. By using Excel to get the salinity-morphology changes relationship with the various rainfall intensity by plotting the graph.

Fig. 1. The flow chart of the research methodology

A laboratory investigation has been conducted in a straight channel in order to observe the mixing between saltwater (estuary) and freshwater (river). Freshwater run from one end of the straight channel, overflowing the weir at the other end. Saltwater was mixed up with a red dye tracer and released through the weir, where it will be pushed upstream by gravity. Plotted graphs are used to examine the spatial and temporal salinity patterns in the flume. The results show differences occurred due to the freshwater inflows and saltwater intrusion. This illustrated the typical salt-wedge estuary characteristics. In this research, there are two types of experiments have been conducted for different morphology changes in order to get spatial and temporal data collection. The mixing between fresh water and salt water for this research is shown in Figure 2. Salt water that is represented by a red dye tracer is discharged through pipelines to the weir and were flowing in the opposite direction of the freshwater flow in an open channel. Fresh water flowed at the normal depth, $y_0 \approx 20$ cm. The laboratory investigations were conducted using a flume channel model with an effective length of 500 cm, 30.7 cm wide, and 50 cm deep in order to represent the idealised estuary. In this experiment, the freshwater inflow was represented as rainfall patterns.

During the laboratory experiments, sampling stations were established in horizontal (*x*-axis), transverse (*y*-axis), and vertical (*z*-axis) directions for the purpose of analysis and discussions. The salinity level at each station was then measured using a conductivity meter (water quality checker).

The locations of the sampling station based on the *x*-axis, *y*-axis, and *z*-axis are given in Table 1, Table 2, and Table 3, respectively. All the locations (*x*-, *y*-, and *z*-axis) and the experimental durations (240 seconds with a 40-second interval) are chosen in order to analyse the salt water – fresh water mixing behaviour in spatial and temporal distributions.

Table 1
Location of the sampling stations based on the *x*-axis

Station	Distance from weir, *x* (cm)
1	50
2	150
3	400

Table 2
Location of the sampling stations based on the *y*-axis

Station	Distance from weir, *y* (cm)
1	0
2	15
3	30

Table 3
Location of the sampling stations based on the *z*-axis

Station	Distance from weir, *z* (cm)
1	5
2	8
3	15

At each station, the water samples were taken at the water surface, in the middle, and at the bottom for every 40 seconds interval with a total duration of 240 seconds. Samples were also taken from three different positions, namely in the central part of the water flow and near the channel wall (right and left directions from the channel wall). Therefore, the station has nine sampling points at different positions for each station.

3. Results and Discussion

3.1 Observation of Salinity Pattern

According to [15], in a real estuarine system, the dispersion is highest near the estuary mouth and decreases in an upstream direction. It is because the gravitational circulation is proportional to the density gradient, the gravitational dispersion reduces with the salinity gradient until it becomes very small near the toe of the intrusion curve. The changes in salinity along the open channel can be observed at the different dispersion patterns of salinity at three locations of observations, x_1 = 0.5 m, x_2 = 1.5 m, and x_3 = 4.0 m. Figure 2 illustrates the pattern at station 3 which is located at the most upstream, near the freshwater tank. The difference in salinity level between heavy and light rain conditions with morphology effect can be seen in Figure 3 and Figure 4.

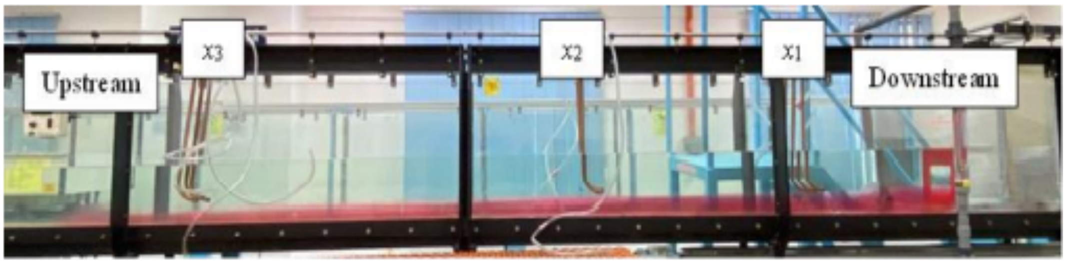


Fig. 2. Concentration of red dye tracer (salt water) without morphology effect

Fig. 3. Concentration of red dye tracer during heavy rainfall conditions with morphology effect (represent by artificial roughened bed section)

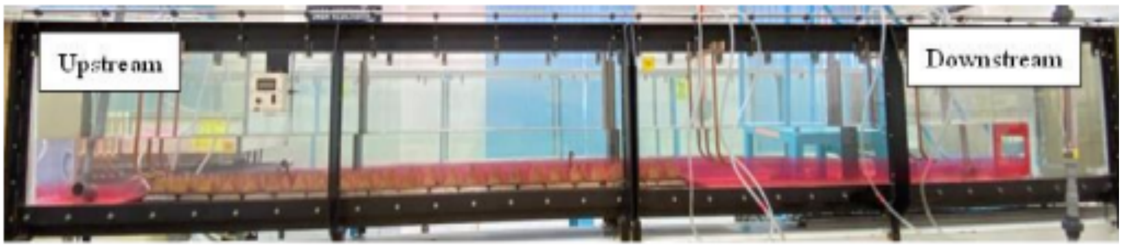
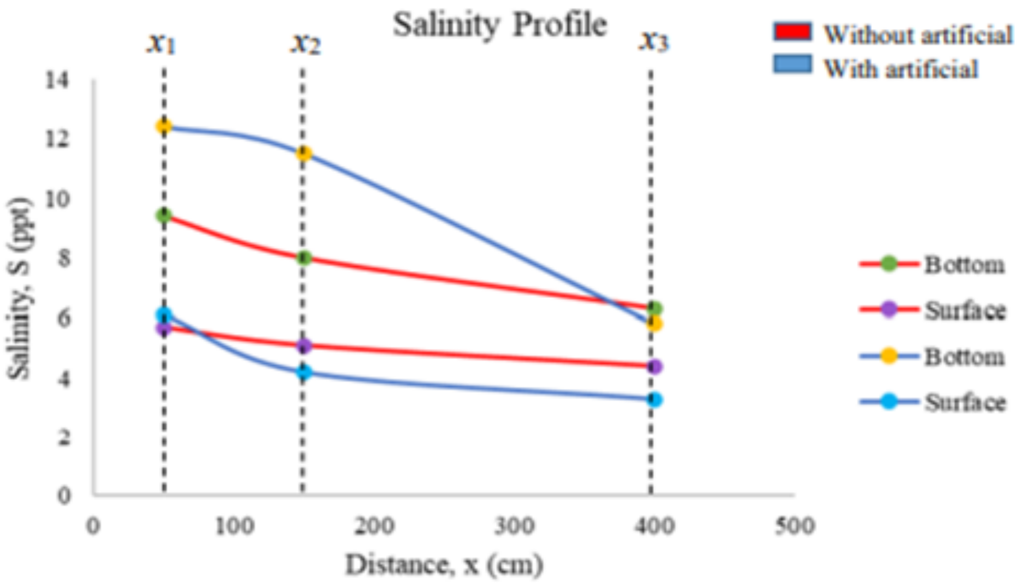


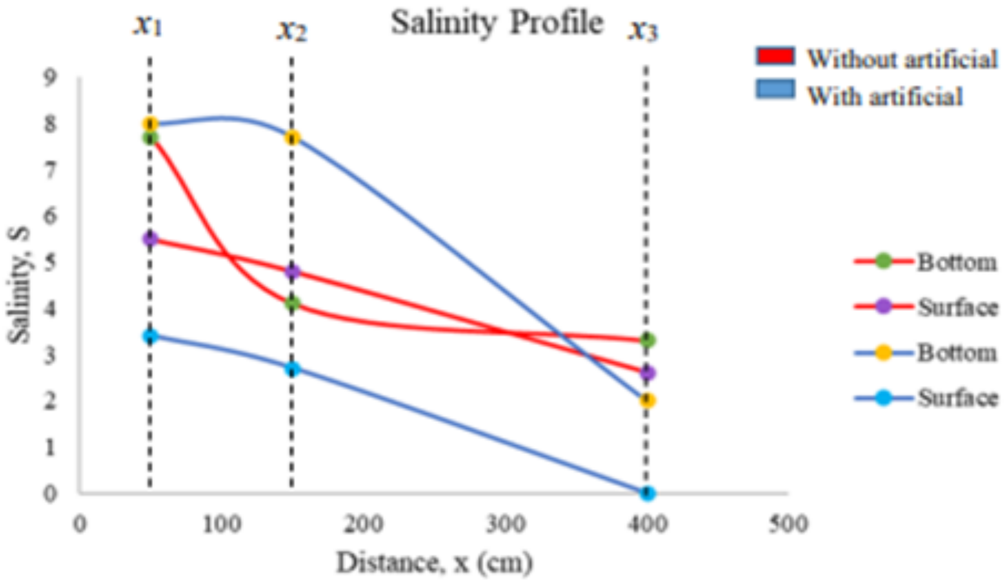
Fig. 4. Concentration of red dye tracer during light rainfall conditions with morphology effect (represent by artificial roughened bed section)

3.2 Longitudinal Salinity Profile

Significant difference in terms of salinity due to the change of morphology has been confirmed as seen in Figure 5 where the salinity level with artificial roughened bed section is lower compared without the presence of artificial during different rainfall condition. The reason might be caused by increasing of salinity at downstream, because it tends to accumulate at the downstream of the channel. Therefore, the presence of artificial roughened bed section influenced in the mixing of fresh water and salt water in estuarine system where the higher the flowrate of freshwater, the lower the salinity level. Thus, artificial roughened bed section may cause the salt water to move slower to the upstream.



(a) Salinity changes with and without bed level changes during light rainfall condition

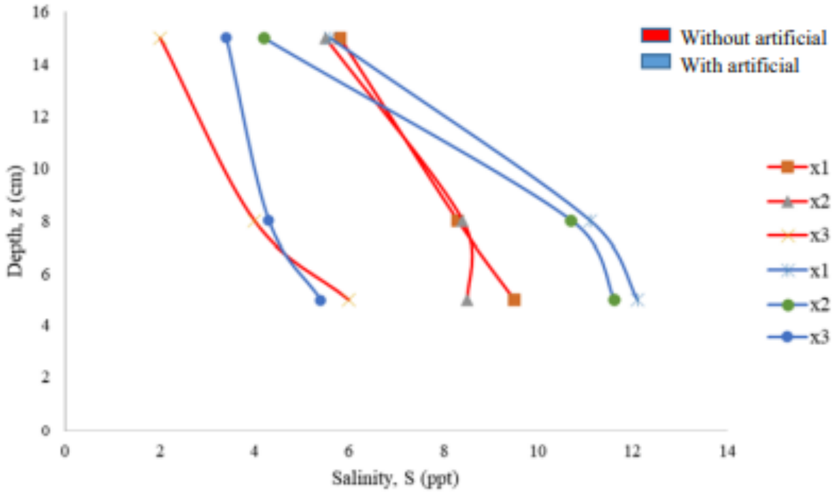


(b) Salinity changes with and without bed level changes during heavy rainfall condition

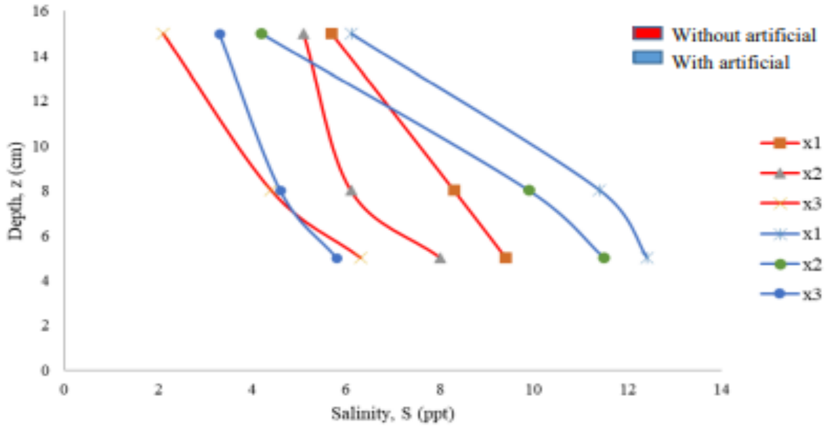
Fig. 5. Salinity profiles along the channel length starting from station x_1 (downstream), x_2, and x_3 (upstream) at different bed levels for different rainfall conditions

3.3 Salinity Characteristics and Profile at Various Depths

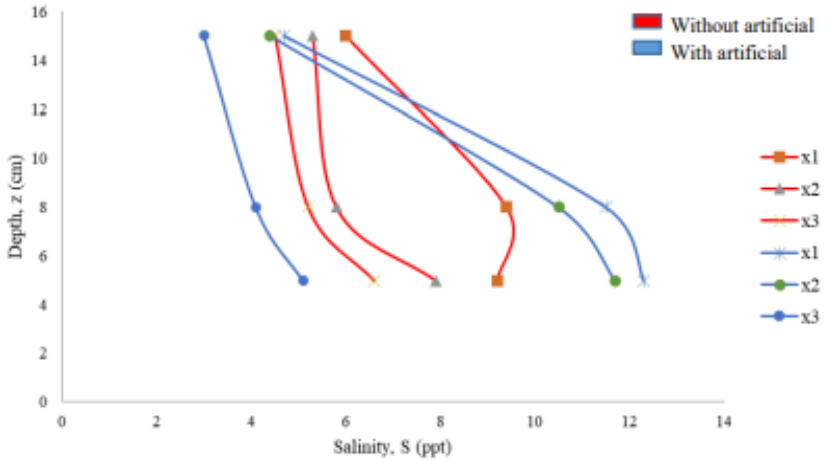
The density and gravitational factors were defined to have the most influence on the differences that occurred in salinity profiles due to depth. Freshwater tended to float on top of the water flow because of its lower density, while salt water is likely to move along the mid-depth and the channel bottom. The bottom was then having higher salinity rather than in surface water. Based on Figure 6 and Figure 7, the salinity changes for all graphs plotted were almost similar where the lower the depths, the higher the salinity level.



(a) Station y_1 = 0 cm (near to channel wall)

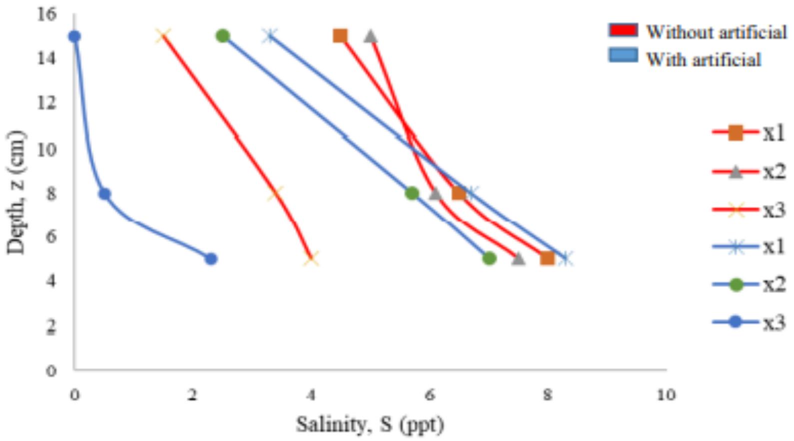


(b) Station y_2 = 15.0 cm

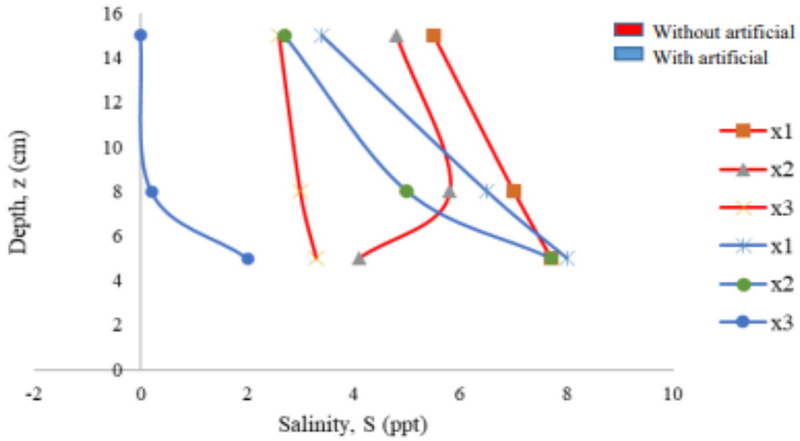


(c) Station y_3 = 30.0 cm (near to channel wall)

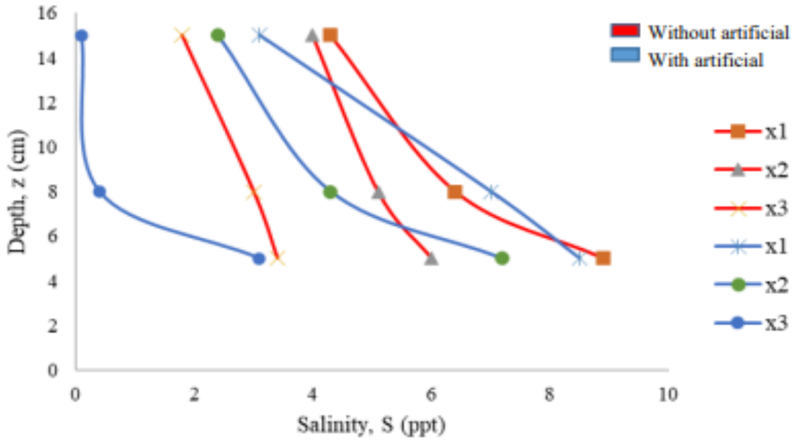
Fig. 6. Salinity profiles at selected station versus depth in y direction during light rainfall conditions with and without artificial roughened bed section



(a) Station y_1 = 0 cm (near to channel wall)



(b) Station y_2 = 15.0 cm



(c) Station y_3 = 30.0 cm (near to channel wall)

Fig. 7. Salinity profiles at selected station versus depth in y direction during heavy rainfall conditions with and without artificial roughened bed section

3.4 Temporal Salinity Profile

The duration of salt water to move and mix with fresh water from downstream (x_1 = 0.5 m) to upstream (x_3 = 4.0 m) is approximately 240 seconds or close to 4 minutes. The dispersion and the movement of the mixing process that occurs can be examined according to the salinity changes that occur in each station. According to Figure 8, the trend for the salinity changes at different morphology from x_1, x_2, and x_3 is almost similar to Figure 9.

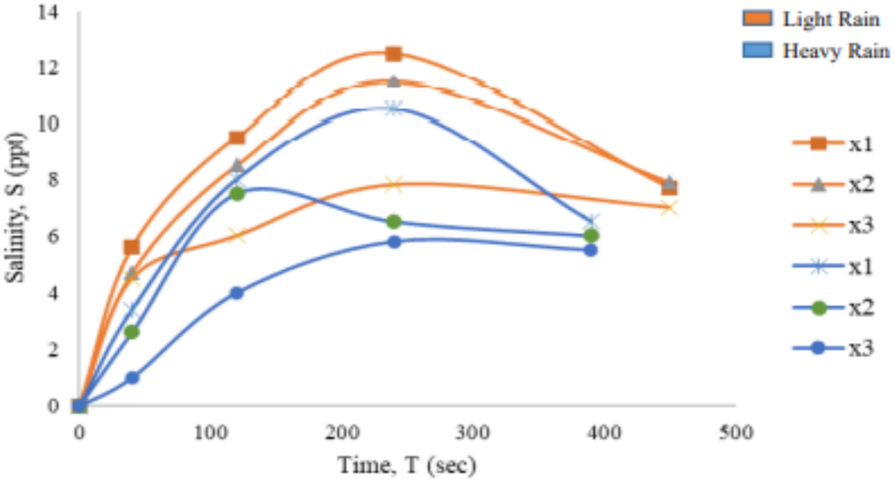


Fig. 8. Temporal pattern of salinity at stations x_1, x_2, and x_3 without artificial roughened bed section for different rainfall conditions

Nevertheless, Figure 9 shows the time taken for the salinity to reach equilibrium at the artificial roughened bed section is faster. It can be seen that during heavy rainfall, the salinity level is decrease upstream, hence the time taken also decrease in order to achieve equilibrium. As can be concluded when artificial roughened bed section affects the time taken for salinity to reach an equilibrium state. Meanwhile, morphology changes also affect the mixing of fresh water and salt water.

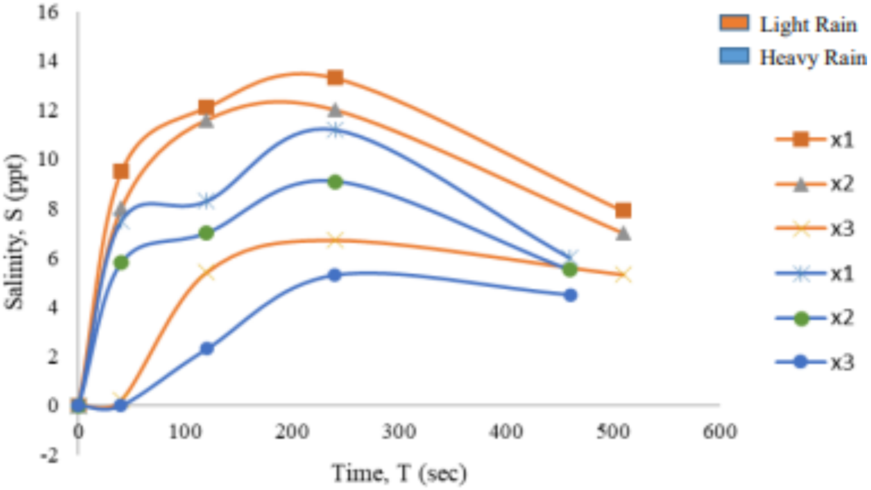


Fig. 9. Temporal pattern of salinity at stations x_1, x_2, and x_3 with artificial roughened bed section for different rainfall conditions

4. Conclusions

Overall, based on laboratory investigation on the idealised estuary in morphology changes for different rainfall conditions, it can be summarised that the flume channel is suitable for the purpose to analysed the morphological changes in bed level and surface roughness and the changes in salinity levels horizontally (*x*-axis), and in the transverse direction (*y*-axis) as the main objective.

From the results, it can be concluded that there are differences in salinity during light rainfall and heavy rainfall condition where salinity during heavy rainfall is lower compared to light rainfall. In this finding, the artificial roughened bed section also affects the salinity pattern during the high and low flow of rainfall intensity whereas the artificial roughened bed section caused the mixing process between fresh water and salt water to occur slowly upstream and quickly downstream.

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