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Investigating Salinity Variation in Estuarine System: Effects of Upstream Water Levels – A Laboratory Study

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ABSTRACT

Estuaries, where freshwater rivers converge with saline ocean water, play vital roles in supporting marine life and human civilization. This study examines salinity dynamics in estuarine systems, focusing on the impact of upstream water level changes on saltwater intrusion. Through experimental manipulation in an idealised channel, varying water depths upstream were simulated. With a 15cm and 30cm differential in the water level upstream, freshwater flows from one end of the flume overflowing a moveable weir at the other end. The saline water combined with a red-coloured tracer to differentiate saltwater from freshwater, where the movement and distribution of saltwater may be roughly observed throughout the experiment and pulled upstream by the force of gravity. The analysis of the investigation was done spatially and temporally in order to determine the salinity mixing in the longitudinal, horizontal, and vertical at different heights of upstream water level. Analysis revealed that higher upstream water levels led to decreased salinity levels due to increased freshwater flow. The water level was influenced and affected the time taken for salinity to reach an equilibrium state. Hence, the higher the water level of upstream, the lower the salinity level. Findings underscore the importance of understanding how estuarine salinity is influenced by upstream conditions for effective management and conservation efforts.

Keywords: Estuarine system; Salinity dynamics; Upstream water levels; Saltwater intrusion; Experimental manipulation; Idealised channel

INTRODUCTION

Estuaries, defined as coastal bodies of water where freshwater rivers merge with saline ocean water, represent critical ecosystems supporting marine life and human activities (Pein et al. 2018). These dynamic environments exhibit complex salinity dynamics influenced by various factors including tidal forces, stream flow, and water density variations (Ali et al. 2024; Izam et al. 2024; Kuijper & Rijn 2011; Nuryazmeen 2018; Nuryazmeen et al. 2013; Nuryazmeen & Tahir 2014). The intrusion of saltwater into estuaries, known as salt intrusion, occurs when denser ocean water penetrates the typically freshwater regions of the estuary, impacting its ecological balance. Additionally, anthropogenic factors such as pollution from point and nonpoint sources further exacerbate salinity fluctuations, posing threats to estuarine ecosystems (Hii et al. 2006; Sulaiman et al. 2021; Zaikowski et al. 2008). According to Izam et al. (2024) and Nuryazmeen (2018), variations in freshwater inflow from rivers can alter the salinity gradient within estuaries, with increased freshwater discharge reducing salt intrusion and creating stratified water layers. However, previous studies have highlighted a lack of detailed analysis using laboratory experiments to examine specific factors affecting the salinity dynamics, such as water level variations that lead to changes in salinity.

The interplay between salinity, temperature, and water density shapes the hydrodynamics of estuarine systems, influencing mixing processes and ecological dynamics. Understanding the impact of freshwater inflow on salinity variation is crucial for effective management and conservation of estuarine habitats. While estuaries experience fluctuations in salinity levels during tidal cycles, human activities such as river flow regulation can also alter salinity patterns, affecting ecosystem health and function (Balasuriya 2018; Bricheno et al. 2021; Hoagland et al. 2020; Kumar et al. 2020; Scanes et al. 2020).

Laboratory studies play a pivotal role in elucidating the complex interactions between upstream freshwater inputs and salinity intrusion dynamics in estuarine systems. By simulating various water level scenarios, these experiments provide insights into the mechanisms driving salinity changes and their ecological consequences. Consequently, integrating findings from such studies into salinity modelling efforts is essential for developing robust management strategies that consider both natural and anthropogenic influences on estuarine ecosystems. Thus, this paper illustrates the identification of salinity changes due to various upstream water levels, both temporally and spatially (in the longitudinal, horizontal, and vertical directions) in estuarine systems, and the determination of salinity-various upstream water levels relationships.

METHODOLOGY

An experimental study was carried out in a flume to identify the process of mixing in a salt-wedge estuary. A saltwater gravity current is created by allowing saltwater to reach the bottom of an overflow weir at one end of the channel, causing it to flow upstream. Mixing will occur concurrently in the *x*-axis, *z*-axis, and *y*-axis directions within the idealised straight channel. The spatial and temporal distribution of saltwater intrusion mixing patterns was investigated by using red colour tracers. The salinity profiles in the flume channel are analysed using the plotted graphs to enhance understanding of spatial and temporal variations. The research methodology flowchart for the salinity variation laboratory study due to upstream water levels is shown in Figure 1**.**

Experimental investigations were carried out in an idealised straight channel to investigate the process of freshwater (river) and saltwater (estuary) mixing under various upstream freshwater levels. Fresh water flows constantly from one end of the straight channel to the opposite end, flowing over the weir. Before its discharge through the weir, the saline water is combined with a red-coloured tracer and then pulled upstream by the force of gravity. The investigation focused on the spatial and temporal salinity patterns involved with the plotted graphs to gain a more thorough understanding of the mixing mechanism.

Two experimental conditions were carried out for this experiment, with a different water level at the upstream location. In the first condition, fresh water flowed at a depth of 15cm, while in the second condition, it flowed at a depth of 30cm. The maximum freshwater flow rates are determined by measuring the maximum freshwater depth. This was done to collect spatial and temporal data.

The red-coloured tracer is used for showing the flow of salt water, which is discharged through pipelines into the weir. This saltwater flows in the opposite direction of the freshwater flow in an open channel. The laboratory investigation was conducted using a flume channel model with an effective length of 500 cm, a width of 30.7 cm, and a depth of 50 cm to imitate an idealised estuary.

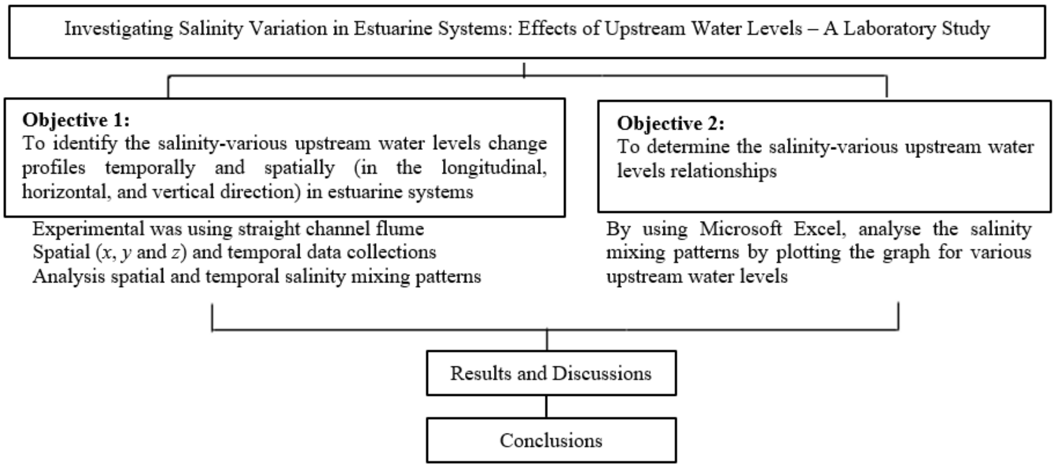


FIGURE 1. Flowchart of research methodology

The locations of the sampling stations are shown in Figure 2, Table 1, 2, and 3, respectively, according to the *x*-axis, *y*-axis, and *z*-axis. A conductivity meter was used to determine the salinity level at each station (water quality checker).

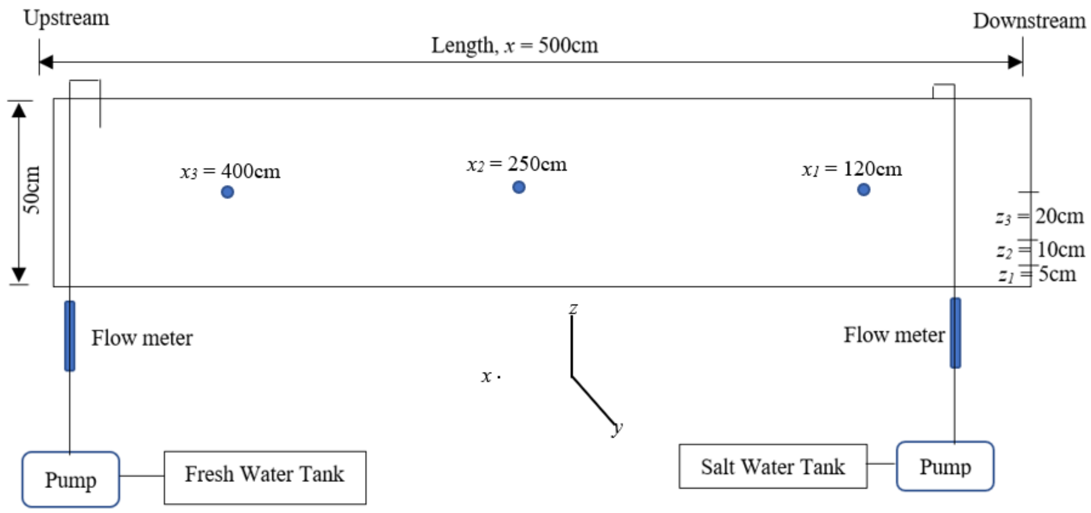


FIGURE 2. Front view of an experimental layout for 15 cm and 30 cm upstream water level conditions

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

Station	Distance from weir, *x* (cm)
1	120
2	250
3	400

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

Station	Distance from channel wall, *y* (cm)
1	7.5
2	16.5
3	25.5

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

Water depth, *H* (cm)	Station	Distance from channel bed, *z* (cm)
15	1	5
	2	10
30	2	10
	3	20

At every station (*x*- and *y*-directions), water samples were taken at two places (vertically, *z*-direction) which were at the bottom and surface with 54 seconds time duration for 15cm and 30cm upstream water level conditions. The sample was also taken from three stations (*y*-direction) which were in the centre of the flume and near the channel wall.

RESULTS AND DISCUSSION

SALINITY PATTERN

The salinity changes along the open channel can be evaluated by determining the different salinity mixing dispersion patterns at three longitudinal sampling stations, which are x_1=0.12m, x_2=0.25m, and x_3=0.4m in two different upstream water levels (15cm and 30cm upstream water levels). The salinity, *S*, is shown the highest at station x_1, which is located downstream near the saltwater discharge point. The salinity level gradually decreases at the following station, x2, and finally reaches the lowest salinity, S, at station x3, which is upstream and close to the freshwater discharge point. In an actual estuarine system, the salinity dispersion is greatest close to the estuary mouth and decreases upstream (Izam et al. 2024; Nuryazmeen 2018). The presence of high salinity is seen in the bottom part of the channel, whereas the higher layer reaching the water surface presents low salinity as shown in Figure 3. The reason for this is due to the density of salt water is greater than the density of freshwater.

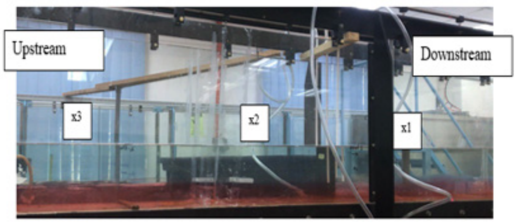


FIGURE 3. Saltwater (red colour) mixed with 15 cm and 30 cm upstream freshwater level

LONGITUDINAL SALINITY PROFILE

Referring to Figure 4, the plotted graph shows that the highest salinity level occurs downstream near the salt water discharge point at station x_1 for both upstream water level conditions (15cm and 30cm upstream water levels). The graph illustrates that the salinity level is higher for the 15cm upstream water level condition compared to the 30cm upstream water level condition. In addition, the salinity levels decrease from downstream (x_1) to upstream (x_3) for both water level conditions. This is because the water level from upstream affects the salinity by either diluting or concentrating it as dispersion and advection processes occur during the mixing between saltwater and freshwater (Ali 2024; Nuryazmeen et al. 2013). The increased water levels in the upstream area may result in the dilution of salinity downstream, whereas low freshwater levels might cause increased salinity due to lower dilution. With reduced dilution, the existing salt content becomes more concentrated, leading to higher salinity levels.

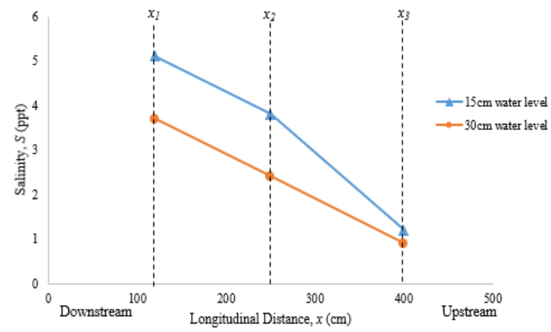


FIGURE 4. Salinity profiles from downstream to upstream due to 15cm and 30cm upstream water level

SALINITY CHARACTERISTICS AND PROFILES AT VARIOUS DEPTHS

The variations in salinity profiles due to depth are primarily impacted by gravitational and density factors. Freshwater, because of its lower density, tends to float on the surface of the water flow, while salt water is more likely to flow along the bottom and middle layers of the channel. Thus, the bottom had higher salinity rather than in surface water as illustrated in Figure 5 from both 15cm and 30cm upstream water level conditions. The findings show the changes of salinity relatively from the surface to the bottom along the channel.

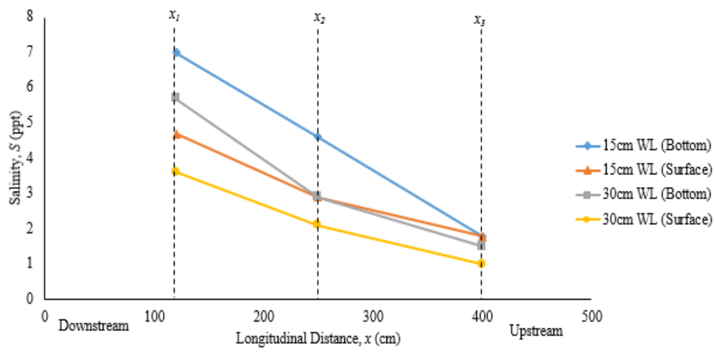


FIGURE 5. Salinity profiles at various depths (bottom and surface) for 15cm and 30cm upstream water level conditions

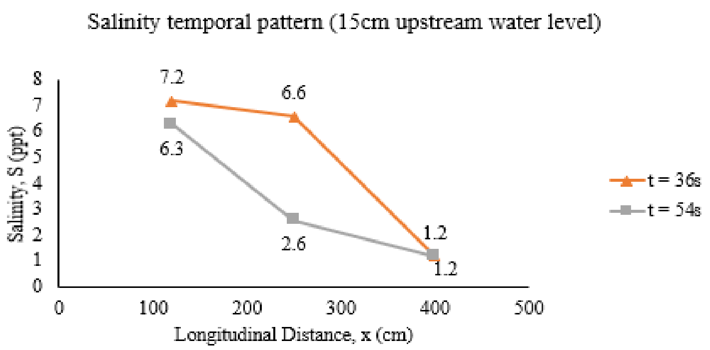
In accordance with the nature of the denser salt water, it can be determined that at the bed channel, S is the highest. Meanwhile, salinity on the surface is the lowest as the salt water is diluted by the fresh water.

TEMPORAL SALINITY PROFILE

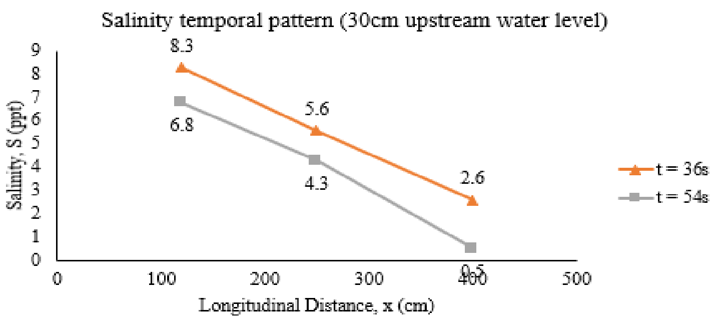
The temporal salinity patterns were recorded for t_1 = 36s and t_2= 54s for both conditions, 15cm and 30cm upstream water level from downstream to upstream direction. The dispersion and the movement of the mixing process that occurs can be examined according to the salinity changes that occur in each station.

In this experiment, saltwater intrusion was influenced by a few basic factors. They are density, flow rate discharges differential, friction, and shear velocity. When the salt water was let to contact with the freshwater, it was obvious that the salinity level was high downstream, x_1 for both 15cm and 30cm upstream water level conditions. The salinity level then was gradually decreased at the next station (x_2) to upstream (x_3) for t_1 and t_2 as depicted in Figure 6. Through the graph, S is high at the early stage (t_1 = 36 seconds) in the downstream area, while S is decreased upstream (x_3) as the the station is near to the source of freshwater discharge. In x_1, S is the highest value because of the closest to the source of the saltwater discharge for both conditions.

Furthermore, the graph of Figure 6a (15 cm upstream water level) and Figure 6b (30cm upstream water level) show how the value of S is initially high (t_1) at the downstream (x_1) and then decreased at t_2. Meanwhile, the salinity levels at t_1 and t_2 continuously reduce from downstream to upstream as the mixing occurs. This provides evidence for the occurrence of salinity intrusion in the channel. It is similar to the real situation in estuarine system when the mixing occurs, the salinity level will change from the river mouth to the upstream as several factors induce the phenomenon, such as freshwater flow, density difference, the salinity dispersion, the gravitational circulation, and also the longitudinal salinity gradient (Geyer & Maccready 2014; Park et al. 2008; Syuhaida & Gisen 2021).



Salinity temporal pattern due to 15cm upstream water level



Salinity temporal pattern due to 30cm upstream water level

FIGURE 6. Salinity temporal pattern from downstream to upstream due to (a) 15cm and (b) 30cm upstream water level conditions

The dispersion happened quickly in the early but reduced in the next intervals due to the higher force of fresh water. The movement of saline water is fast for 15 cm water level upstream, because of the freshwater inputs. When freshwater input is low (15cm), an estuary can become as salty as the adjacent ocean. The gravitational circulation and the density of the saltwater are higher than fresh water where it is causing the movement and the mixing process to occur in the middle and bottom channels. Conversely, when the freshwater input is higher (30cm), the estuary can become entirely fresh. This demonstrates that high freshwater inflows can effectively reduce salinity levels, mitigating the intrusion of saltwater.

CONCLUSION

Based on the laboratory investigation of an idealised estuary for 15cm and 30cm upstream water level conditions utilising a straight flume channel is appropriate for the purpose of studying the salinity pattern changes temporally and spatially depending on the water level upstream as the main objective.

Based on the results, the comparison between two different water levels upstream proved. The salinity in the 15cm upstream water level is higher for respective sampling points spatially (horizontal, longitudinal, and vertical directions) and temporally compared to the 30cm upstream water level. Moreover, the findings show the significant influence of upstream water levels on the salinity pattern during the mixing process between freshwater and saltwater. The high upstream freshwater level (30cm) proved that the salinity level decreased rapidly compared to the low upstream freshwater level (15cm).

These findings are beneficial for salinity control through water level management. By regulating upstream freshwater inputs, related water agency can control salinity levels in estuaries. Increasing freshwater discharge during dry periods or in response to salt intrusion events can help maintain a balanced salinity, protecting freshwater species and habitats.

Some recommendations for another related study, such as, the extension of the experimental setup to include more complex estuarine geometries, such as meandering channels, varying depths, and wider cross sections. This will provide a more realistic representation of natural estuarine systems and enhance the understanding of salinity dynamics in diverse environments. Besides, to conduct experiments that simulate seasonal variations in freshwater inflow and tidal cycles. This will help capture the temporal variability in salinity patterns.

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DECLARATION OF COMPETING INTEREST

None.

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