SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Applied Mechanics

Journal homepage:
https://semarakilmu.com.my/journals/index.php/appl_mech/index
ISSN: 2289-7895

Investigation of the Estuarine Salinity-Morphology Characteristics Effects

Nurul Shafiqah Shahrulnizam[1], Nuryazmeen Farhan Haron[1,*], Siti Nurhayati Mohd Ali[1], Noor Suraya Romali[2], Saerahany Legori Ibrahim[3], Mohammad Naser Sediqi[4], Mazlin Jumain[5], Zulkiflee Ibrahim[5]

1 School of Civil Engineering, College of Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
2 Faculty of Civil Engineering Technology, Universiti Malaysia Pahang, 26300 Gambang, Pahang, Malaysia
3 Department of Civil Engineering, Faculty of Engineering, International Islamic University Malaysia, 50728 Gombak, Selangor, Malaysia
4 Green Goal Initiative, Tohoku University, Sendai, Miyagi 980-8577, Japan
5 Faculty of Civil Engineering, Universiti Teknologi Malaysia, Skudai, 81310 Johor Bahru, Johor, Malaysia

ARTICLE INFO

Article history:
Received 17 October 2024
Received in revised form 18 November 2024
Accepted 25 November 2024
Available online 30 December 2024

Keywords:
Salinity intrusion; estuarine salinity-morphology effect characterisation; estuarine system

ABSTRACT

Estuaries, where freshwater rivers meet ocean saltwater, are vital coastal ecosystems characterized by water layer stratification. Human activities, including dredging, industrial waste disposal and coastal development, disrupt estuarine dynamics, leading to altered salinity levels and ecological threats. Sudden salinity changes, often driven by these activities, jeopardize estuarine species adapted to specific salinity conditions, potentially causing biodiversity decline and ecosystem collapse. This research focuses on two cases: Case 1 examines an unaltered estuary, replicating natural conditions, while Case 2 introduces a constriction pattern mimicking real-world estuaries influenced by geological or human-made features. Systematic salinity monitoring along multiple stations, including longitudinal, transverse and vertical directions, reveals a significant correlation between estuary shape and salinity distribution. In Case 2, a central constriction substantially impacts saltwater and freshwater mixing time, resulting in downstream salinity variations. These findings have broader implications, informing environmental conservation, climate adaptation, resource management and infrastructure design. Additionally, they advance fluid dynamics and environmental science, potentially fostering innovation across disciplines. In summary, this research offers practical solutions for the preservation and sustainable development of estuarine ecosystems.

1. Introduction

A coastal water body where freshwater from rivers and streams combines with saltwater from the ocean is known as an estuary [1,2]. Estuaries and the regions that surround them are places where land meets the sea. Despite being influenced by the tides, land features such as barrier islands and peninsulas shield them from the full force of ocean waves, winds and storms [3-8]. Estuaries, as ecotone areas between marine and freshwater environments, are distinguished by a unique combination of physical, chemical and biological characteristics, as well as unusually high production.

* *Corresponding author.*
E-mail address: nuryazmeen@uitm.edu.my

https://doi.org/10.37934/aram.129.1.2431

All estuaries have a constant or intermittent free connection. Based on salinity distribution and stratification, highly stratified, partially mixed and well-mixed estuaries are the most common classifications [9-12]. The distribution of sediments, nutrients and contaminants in a coastal area is influenced by mixing in an estuary, which can vary depending on tidal variations and river discharge.

In estuarine environments, the lower density of fresh river water compared to denser saltwater results in the formation of distinct stratification, where the freshwater floats atop the saltwater upon their confluence. In deep estuaries, this stratification leads to the formation of a salt-wedge estuary, characterized by a sharp interface where denser, saline water from the sea intrudes beneath the less dense freshwater layer. This dynamic allows the saline water to extend further inland beneath the freshwater, while the freshwater flows seaward above the saline layer. The mixing process results in slow changes in salinity distribution across time and space, influenced by tidal impacts, stream flow, water density dissimilarity, estuary characteristics, wind effect and the Coriolis effect [13-18].

When fresh and saltwater collide, mixing occurs in estuaries due to density differences between the two water masses. The density of seawater, determined by salinity and temperature, undergoes significant changes due to the wide salinity range in an estuary and the narrow temperature range. These mixing processes have critical implications for environmental engineering, impacting water quality and ecosystems, including pollution spread, suspended sediment movement, algae blooms and transportation of suspended mining material [19,20].

Moreover, river discharge and tidal levels significantly influence salinity fluctuations in estuaries and environmental factors like wave height and river mouth form can also influence these fluctuations. While research on salinity morphology changes in idealized estuarine systems has been limited, their understanding is crucial for studying the existence and dispersion of species in estuaries.

The present study focuses on elucidating the intricate relationship between estuarine morphology and salinity distribution within estuarine systems. To achieve this, we explore two distinct cases: Case 1, an examination of an ordinary estuary without any constriction and Case 2, an investigation of an estuary with a constriction pattern. These cases serve as proxies for natural estuaries and those influenced by geological or anthropogenic factors, respectively. In Case 1, we consider a wide and unconstricted channel, mirroring a typical estuarine environment. In contrast, Case 2 introduces a central constriction within the channel, simulating the hydrodynamic effects observed in certain real-world estuaries.

Through controlled laboratory experiments, we systematically monitor salinity levels at various points within the estuarine systems, both longitudinally, transversely and vertically, over time. This research aims to shed light on how estuarine morphology influences the mixing processes between saltwater and freshwater, consequently affecting the distribution of salinity. The findings from these experiments are anticipated to offer valuable insights into the resilience and vulnerability of estuarine ecosystems in the face of human-induced alterations and environmental changes. By understanding the dynamic relationship between estuarine morphology and salinity distribution, we can make informed decisions for the conservation and management of these vital coastal ecosystems, preserving their ecological integrity and ensuring the well-being of the communities that rely on them.

2. Methodology

2.1 Experimental Setup

Laboratory tests for this investigation were conducted at the Hydraulics Laboratory in the School of Civil Engineering, Universiti Teknologi MARA. The experiments were carried out in a horizontal flume with a length of 500 cm, width of 30.7 cm and depth of 50 cm, as illustrated schematically in Figure 1.

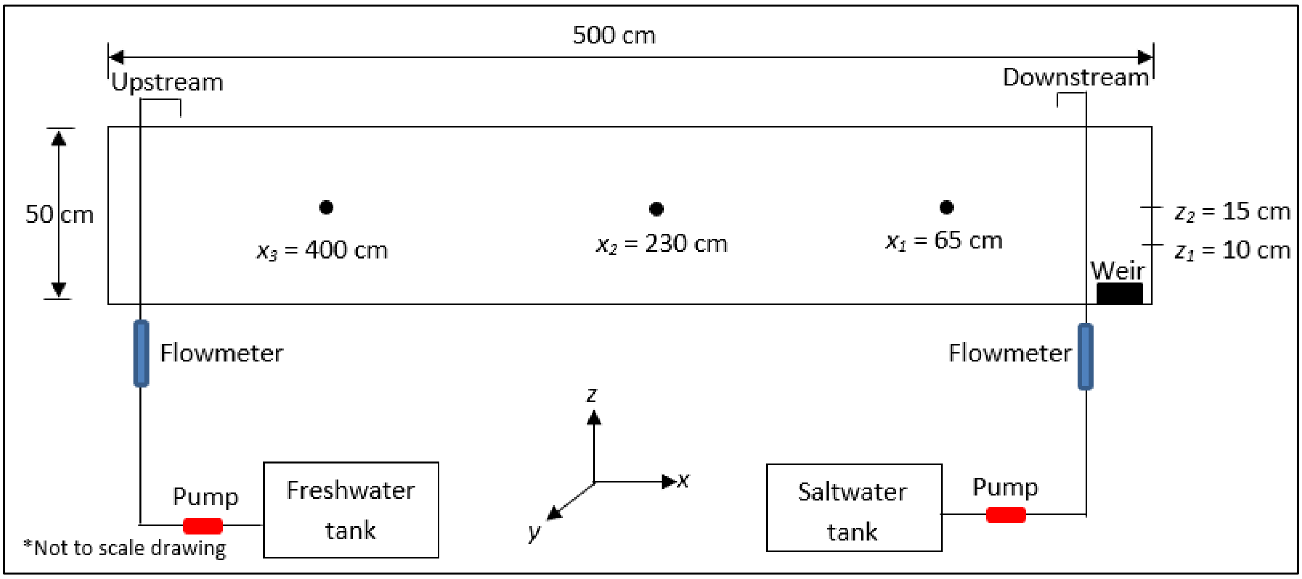

Fig. 1. Front view of the experimental setup

Figures 2(a) and 2(b) depict the top view of the channel for an ordinary estuary (case 1) and an estuary with a contracting central section (case 2).

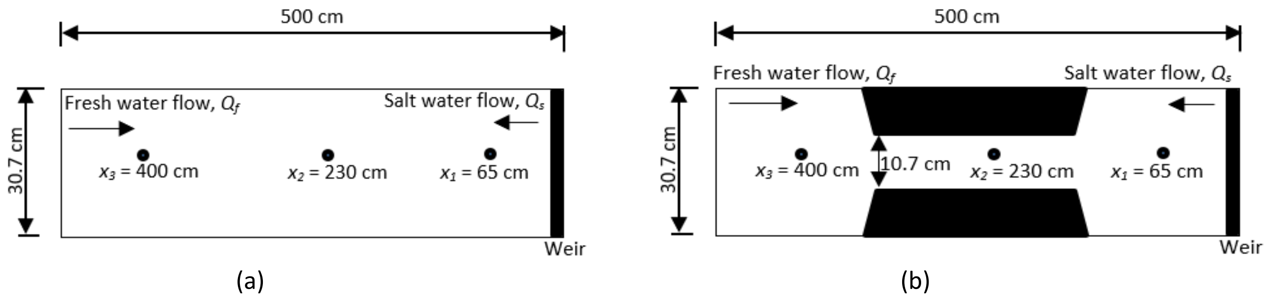

Fig. 2. Plan view (not to scale) of the salinity mixing laboratory investigation for 2 bases; (a) Case 1: ordinary estuary without constriction (b) Case 2: estuary with constriction

To regulate flow rates and maintain a consistent upstream water level in the flume, a suppressed rectangular weir, measuring 30.7 cm in width, 20 cm in height and 10 cm in thickness, was installed at the downstream end. This weir functioned as a flow control barrier, ensuring stable experimental conditions. The water supply system utilized two Polyvinyl Chloride (PVC) tanks: one providing a constant freshwater flow rate of 15 litres per minute and the other supplying a constant saltwater flow rate of 10 litres per minute. The saltwater was prepared by dissolving sodium chloride in tap water to achieve a salinity of 15 parts per thousand (ppt), a critical parameter maintained throughout the investigation.

The experiment started with the release of freshwater from one end of the flume channel and it overflowed at the other end. The water surface elevation along the channel was regularly monitored until an equilibrium flow depth was achieved. At this point, saltwater was slowly introduced at the lower part of the weir, flowing horizontally upstream as a gravity current. To visualize the movement of the saltwater as it mixed with the fresh water in the flume, a red dye tracer was added to the saltwater.

Sample stations were set up in the horizontal (x-axis), transverse (y-axis) and vertical (z-axis) directions for further analysis and discussion. The salinity level at each location was measured using a conductivity meter as a water quality checker. Table 1, Table 2 and Table 3 provide the positions of the sample stations based on the x-axis, y-axis and z-axis, respectively. The selected locations and experimental durations (180 seconds with a 30-second interval) aimed to study the spatial and temporal distributions of the saltwater-freshwater mixing behaviour.

Table 1
Sampling stations in horizontal (x-axis) direction

Station	Distance from weir, x (cm)
x_1	65
x_2	230
x_3	400

Table 2
Sampling stations in transverse (y-axis) direction

Station	Distance from channel wall, y (cm)
y_1	7.5
y_2	16

Table 3
Sampling stations in vertical (z-axis) direction

Station	Distance from channel bed, z (cm)
z_1	10
z_2	15

Water salinity measurements were collected at the surface and the bottom using a siphoning system. The cross-section of the measurement points for each station along the flume is shown in Figure 3.

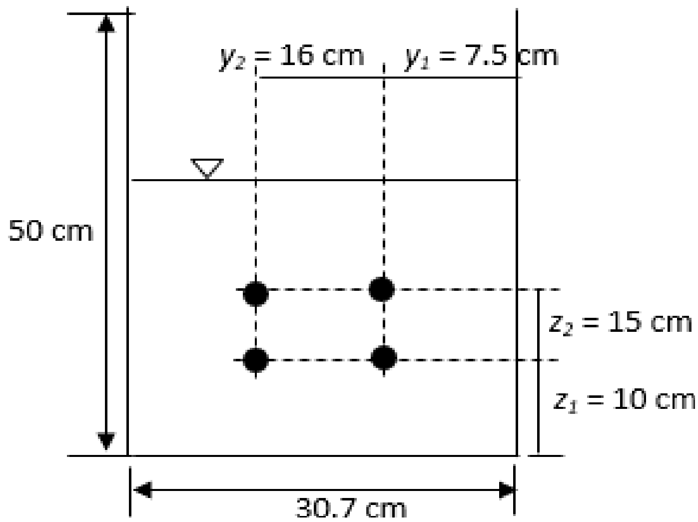

Fig. 3. The cross-section (not to scale) of measurement points for each station along the flume based on y- and z-axis

2.2 Experimental Parameters

The morphological alteration resulting from the contracting cross-section influenced the mixing of estuarine salt and fresh water. To investigate the impact of this contraction, a controlled variable was introduced during the flume test. The first experiment was conducted for the ordinary estuary (Case 1). In the second experiment (Case 2), the flume was modified by reducing each channel side, blocking the cross-section. The parameters applied for both cases in this study are detailed in Table 4.

Table 4
The parameters of Case 1 and Case 2

Parameter	Values
Freshwater discharge, Q_f (l/min)	15
Saltwater discharge, Q_s (l/min)	10
Initial Salinity, S_o (ppt)	15
Total Ambient Flow Depth, H (cm)	18

3. Results and Discussion
3.1 Longitudinal Salinity Profile

Further analysis has identified significant variations in salinity levels between Case 1 and Case 2. The study confirms a substantial difference in salinity due to morphological changes, as illustrated in Figure 4, where the salinity level at the constriction section is lower compared to the section without constriction. This difference is likely due to increased salinity accumulation downstream, where salinity tends to concentrate. The presence of a constriction in the middle of the channel affects the mixing of fresh and saltwater in the estuarine system, with higher freshwater flow rates correlating to lower salinity levels. As a result, the constriction slows the upstream movement of saltwater.

Figure 4 compares salinity profiles along the channel's length at both the bottom and surface water levels, observed at sections from downstream (x_1) to upstream (x_3) with and without constriction. These observations indicate that saline water faces challenges in moving further upstream beyond the constricted central section. The narrowing of the channel creates resistance to upstream flow, leading to salinity accumulation in the downstream section. This phenomenon is well-documented in real-world estuaries, where a decrease in cross-sectional area at the entrance initially weakens tidal strength [21].

Similarly, according to McLean *et al.,* [22], the closure or substantial narrowing of entrances leads to an increase in the water level inside the basin but limits the extent of tidal variation, while open entrances facilitate a consistent and significant exchange of tides with the ocean.

Additionally, the strong discharge of freshwater accelerates the dilution process in the channel. As the channel narrows, the flow velocity of water increases, resulting in greater turbulence and enhanced mixing between saltwater and freshwater, as demonstrated by a study conducted by *et al.,* [21]; Haron *et al.,* [23-25] without any constriction. The narrowing section significantly affects the extent of saltwater intrusion further upstream, as the strong force of freshwater discharge pushes the saltwater downstream. Consequently, in Case 2, the extent of mixing is limited to the contraction section. The dilution of saltwater is attributed to the substantial influx of freshwater. Additionally, the vertical and longitudinal mixing processes taking place within the channel also contribute to the dilution of saltwater.

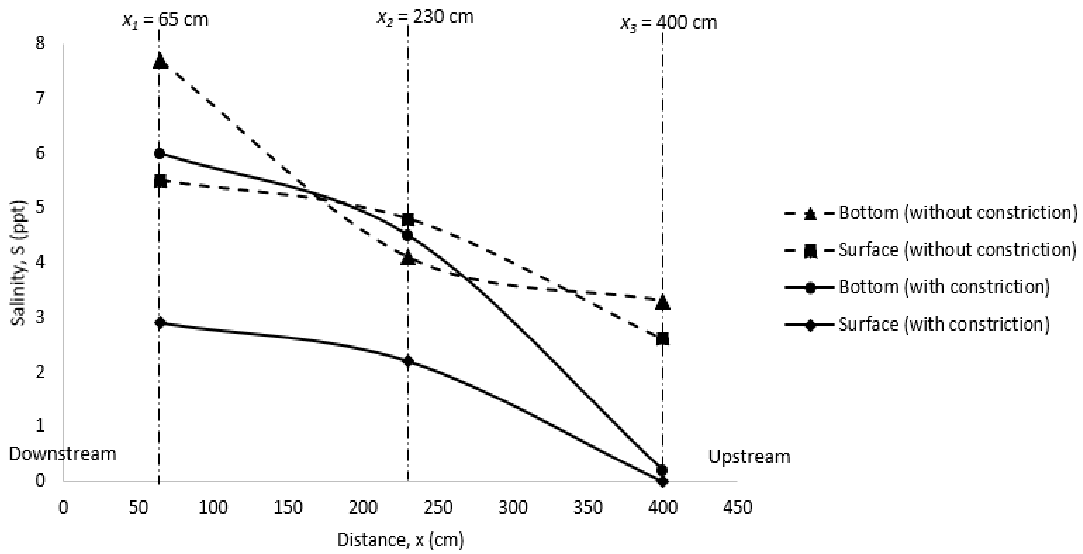

Fig. 4. Salinity profiles along the channel starting from station x_1 (downstream), x_2 and x_3 (upstream) near bottom and surface water levels

3.3 Temporal Salinity Profile

The movement and mixing of saltwater with freshwater from the downstream location (x_1 = 65 cm) to the upstream area (x_3 = 400 cm) occur over approximately 180 seconds or about 3 minutes. This dispersion process is evident through the analysis of salinity changes at each station. Figure 5 illustrates the variations in salinity levels at different stations (x_1, x_2 and x_3) over time.

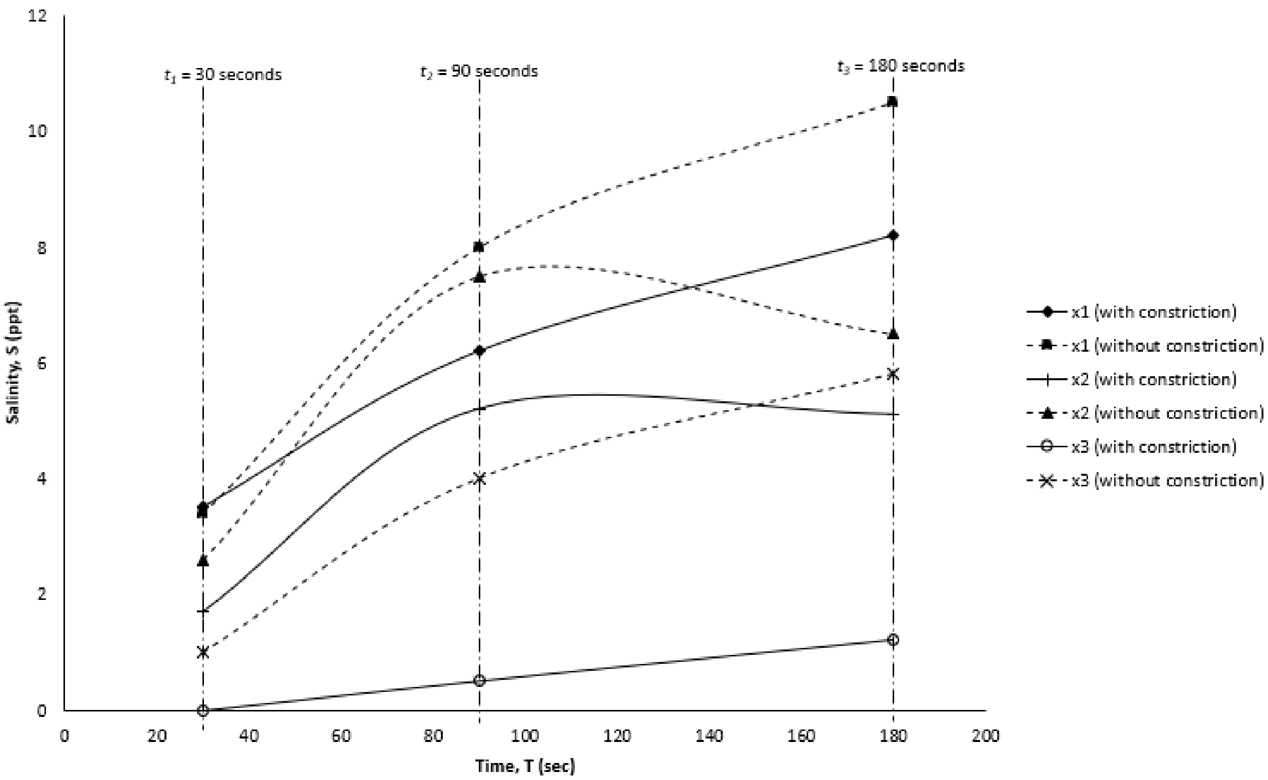

Fig. 5. Temporal pattern of salinity at station x_1, x_2 and x_3 with and without constriction pattern

During the initial stage (t_1 = 30 seconds), the downstream area (x_1) exhibits elevated salinity due to its proximity to the saltwater discharge source. As the water progresses toward the upstream station (x_3), where freshwater discharge dominates, salinity levels gradually decrease. Figure 5 shows that salinity levels decrease spatially from downstream (x_1) to upstream (x_3) for both cases, with and without constriction. However, temporally, salinity levels increase at x_1 and x_3 for both cases, as these locations are unaffected by any constriction. This phenomenon occurs because saltwater flows consistently from upstream to downstream from the start of the experiment (t_1 = 30 seconds) until the end (t_3 = 180 seconds). Meanwhile, in the middle of the channel (x_2), there is a significant reduction in salinity due to mixing with upstream freshwater.

4. Conclusions

In conclusion, our laboratory investigation has provided valuable insights into the dynamics of estuarine salinity mixing influenced by a contracting section. This study concluded that the constriction in the estuarine system will have a significant impact on the salinity pattern while mixing with fresh water. Besides, the findings indicate that salinity levels are typically higher downstream, decreasing gradually upstream, with equilibrium achieved over time, especially near the estuary bottom. Importantly, the presence of a contracting section within the channel effectively limits further upstream intrusion, resulting in elevated salinity levels downstream.

These insights have practical implications across various fields, including environmental conservation, climate adaptation, sustainable resource management and the design of coastal infrastructure projects. This research advances scientific knowledge in fluid dynamics and environmental science, potentially leading to innovative solutions for complex environmental challenges.

Overall, this study provides practical solutions for environmental preservation and sustainable development, emphasizing the importance of understanding estuarine dynamics in the context of human-induced alterations and environmental changes. Future studies may explore specific aspects of estuarine systems in greater depth, examining the long-term ecological impacts and further refining strategies for their protection and management.

Acknowledgement
The authors acknowledge the Ministry of Higher Education (MOHE) and Universiti Teknologi MARA for funding provided under the Fundamental Research Grant Scheme (FRGS) (FRGS/1/2021/TK0/UITM/02/88) and Sustainable Research Collaboration (SRC) 600-RMC/SRC/5/3 (044/2020).

References
[1] Pritchard, Donald W. "What is an estuary: physical viewpoint." American Association for the Advancement of Science, 1967.
[2] Fairbridge, R. W. "The estuary: its definition and geodynamic cycle." *Chemistry and biochemistry of estuaries* (1980): 1-35.
[3] Li, Cheng, Haijia Zhang, Hao Zhang, Bin Sun and Shaolin Yang. "Wave-attenuation and hydrodynamic properties of twin pontoon floating breakwater with kelp." *Applied Ocean Research* 124 (2022): 103213. https://doi.org/10.1016/j.apor.2022.103213
[4] He, Fang, Jindi Li, Jiapeng Pan and Zhiming Yuan. "An experimental study of a rectangular floating breakwater with vertical plates as wave-dissipating components." *Applied Ocean Research* 133 (2023): 103497. https://doi.org/10.1016/j.apor.2023.103497
[5] Sun, Bin, Haijia Zhang, Shaolin Yang and Cheng Li. "Experimental investigation on the wave-attenuating performance and shape optimization of water ballast type floating breakwater." *Ocean Engineering* 248 (2022): 110848. https://doi.org/10.1016/j.oceaneng.2022.110848

[6] Chen, Jiayu, Jinfeng Zhang, Guangyao Wang, Qinghe Zhang, Jitao Guo and Xinmiao Sun. "Numerical simulation of the wave dissipation performance of floating box-type breakwaters under long-period waves." *Ocean Engineering* 266 (2022): 113091. https://doi.org/10.1016/j.oceaneng.2022.113091
[7] Yin, Zegao, Zihan Ni, Yingni Luan, Xuecong Zhang, Jiahao Li and Yao Li. "Hydrodynamic characteristics of a box-type floating breakwater with restrained piles under regular waves." *Ocean Engineering* 280 (2023): 114408. https://doi.org/10.1016/j.oceaneng.2023.114408
[8] Sazali, Ilmi Fatihah and Nuryazmeen Farhan Haron. "Laboratory assessment of a fixed box-type breakwater as temporary coastal protection against wave actions." *Journal of Sustainable Civil Engineering & Technology (JSCET)* 3, no. 1 (2024): 133-144. https://doi.org/10.24191/jscet.v3i1.133--144
[9] Cheng, Peng, Arnoldo Valle-Levinson, Clinton D. Winant, Aurelien LS Ponte, Guillermo Gutierrez de Velasco and Kraig B. Winters. "Upwelling-enhanced seasonal stratification in a semiarid bay." *Continental Shelf Research* 30, no. 10-11 (2010): 1241-1249. https://doi.org/10.1016/j.csr.2010.03.015
[10] Haron, Nuryazmeen Farhan. "Modelling of salinity intrusion for transverse flow during extreme flood event in Kuala Selangor." PhD diss., Universiti Teknologi MARA, 2018.
[11] Haron, N. F. and W. Tahir. "Hydrodynamic and Salinity Intrusion Model in Selangor River Estuary." In *IOP Conference Series: Materials Science and Engineering*, vol. 136, no. 1, p. 012083. IOP Publishing, 2016. https://doi.org/10.1088/1757-899X/136/1/012083
[12] Haron, Nuryazmeen Farhan and Wardah Tahir. "Simulation of Estuary Transverse Flow Salinity Intrusion During Flood Event: Case Study of Selangor River Estuary." In *ISFRAM 2015: Proceedings of the International Symposium on Flood Research and Management 2015*, pp. 141-149. Springer Singapore, 2016. https://doi.org/10.1007/978-981-10-0500-8_12
[13] Dellar, Paul J. and Rick Salmon. "Shallow water equations with a complete Coriolis force and topography." *Physics of fluids* 17, no. 10 (2005). https://doi.org/10.1063/1.2116747
[14] Stewart, A. L. and P. J. Dellar. "Two-layer shallow water equations with complete Coriolis force and topography." In *Progress in Industrial Mathematics at ECMI 2008*, pp. 1033-1038. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010. https://doi.org/10.1007/978-3-642-12110-4_164
[15] Murillo, Javier, Borja Latorre and Pilar García-Navarro. "A Riemann solver for unsteady computation of 2D shallow flows with variable density." *Journal of Computational Physics* 231, no. 14 (2012): 4775-4807. https://doi.org/10.1016/j.jcp.2012.03.016
[16] Narváez, Diego A. and Arnoldo Valle-Levinson. "Transverse structure of wind-driven flow at the entrance to an estuary: Nansemond River." *Journal of Geophysical Research: Oceans* 113, no. C9 (2008). https://doi.org/10.1029/2008JC004770
[17] Li, Yun and Ming Li. "Wind-driven lateral circulation in a stratified estuary and its effects on the along-channel flow." *Journal of Geophysical Research: Oceans* 117, no. C9 (2012). https://doi.org/10.1029/2011JC007829
[18] Uncles, Reginald J. and John A. Stephens. "The effects of wind, runoff and tides on salinity in a strongly tidal sub-estuary." *Estuaries and coasts* 34 (2011): 758-774. https://doi.org/10.1007/s12237-010-9365-3
[19] Azhikodan, Gubash, Nay Oo Hlaing, Katsuhide Yokoyama and Masashi Kodama. "Spatio-temporal variability of the salinity intrusion, mixing and estuarine turbidity maximum in a tide-dominated tropical monsoon estuary." *Continental Shelf Research* 225 (2021): 104477. https://doi.org/10.1016/j.csr.2021.104477
[20] Izam, Tengku Fadhlin Tengku Mohmed Noor, Nuryazmeen Farhan Haron, Siti Nurhayati Mohd Ali, Noor Suraya Romali and Saerahany Legori Ibrahim. "Idealised Estuary Salinity-Morphology Effect Characterisation Investigation." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 42, no. 1 (2024): 93-103. https://doi.org/10.37934/araset.42.1.93103
[21] Ali, Siti Nurhayati Mohd, Nuryazmeen Farhan Haron, Zulkiflee Ibrahim, Mazlin Jumain, Md Ridzuan Makhtar, Wan Nor Afiqa Wan Mustafah Kamal and Azanni Nur Izzati Jamaludin. "Salinity-Various Flow Characteristics Investigation in an Identical Meandering Channel." *CFD Letters* 16, no. 3 (2024): 28-36. https://doi.org/10.37934/cfdl.16.3.2836
[22] McLean, Errol J. and Jon B. Hinwood. "Application of a simple hydrodynamic model to estuary entrance." *Coastal Engineering Proceedings* 32 (2010): 42-42. https://doi.org/10.9753/icce.v32.management.42
[23] Haron, Nuryazmeen Farhan and Wardah Tahir. "Physical model of estuarine salinity intrusion into rivers: A review." *Advanced Materials Research* 905 (2014): 348-352. https://doi.org/10.4028/www.scientific.net/AMR.905.348
[24] Nuryazmeen, F. H., T. Wardah and N. M. Irma. "Laboratory investigations on estuary salinity mixing: preliminary analysis." *Int. J. Sci. Basic Appl. Res.(IJSBAR)* 13, no. 1 (2014): 36-41.
[25] Haron, Nuryazmeen Farhan, Wardah Tahir, Irma Noorazurah Mohamad, Lee Wei Koon, Jazuri Abdullah and Natasya Anom Sheikh Aladin. "Salinity Velocity Pattern in Estuary Using PIV." In *ISFRAM 2014: Proceedings of the International Symposium on Flood Research and Management*, pp. 221-243. Springer Singapore, 2015. https://doi.org/10.1007/978-981-287-365-1_19