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Unraveling the Impact of Rainfall Variability on Estuarine Salinity Dynamics: Insights from Experimental and Numerical Modelling Approaches

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ABSTRACT

This study investigates the influence of rainfall patterns on salinity dynamics in estuarine environments through laboratory experiments and MIKE21/3 numerical modelling. A meandering channel simulated varying freshwater flow rates (2.4 L/s, 3.2 L/s, and 4.8 L/s) representing low, moderate, and heavy rainfall scenarios. The study aims to quantify how rainfall-induced freshwater inflows affect salinity intrusion length and concentration in meandering estuaries, and to validate experimental results with numerical modelling. Salinity measurements were taken across multiple cross-sections and depths, supported by tracer visualization, and further analyzed using MIKE 21/3 simulations calibrated against observed data. Model performance was evaluated using R^2, NSE, and RMSE statistical indicators. Results show that increased freshwater discharge significantly reduces salinity intrusion length, with heavy rainfall decreasing salinity intrusion by up to 30%. Meander bends generated localized salinity gradients due to secondary circulation. The MIKE 21/3 model strongly validated experimental findings ($R^2 > 0.9$; NSE > 0.5), confirming its robustness in replicating estuarine salinity dynamics. Unlike previous studies which emphasized straight channels or large-scale rainfall data from remote sensing, this research integrates controlled flume experiments with three-dimensional modelling in a meandering channel. This combined framework provides new insights into tropical rainfall–salinity interactions, addressing a key research gap and offering practical contributions for estuarine water management under climate change.

Keywords: Salinity dynamics; rainfall impact; estuarine environments; MIKE 21/3 modelling; laboratory experiments

INTRODUCTION

Estuaries are dynamic transitional zones where freshwater from rivers mixes with saltwater from the ocean, creating unique and complex ecosystems. These regions serve as crucial habitats for a wide range of marine and freshwater species, acting as breeding and nursery grounds for commercially important fish and shellfish. The delicate balance of estuarine environments is maintained by the interactions of tidal forces, river discharge, and meteorological conditions such as rainfall patterns (Dyer 1997; Hoagland et al. 2020; Khojasteh et al. 2021; Liu et al. 2020; Nuryazmeen & Tahir 2014). Understanding these dynamics is critical for managing water quality, sustaining aquatic ecosystems, and supporting human activities such as agriculture, fisheries, and urban development in estuarine regions (Ali et al. 2024; Izam et al. 2024; Largier 1993; Mahamood et al. 2024; Shahrulnizam et al. 2024). However, the increasing variability in global climate patterns, particularly changes in rainfall, poses significant challenges to estuarine systems.

Climate change is altering rainfall patterns worldwide, leading to more frequent and intense rainfall events (Balaian et al. 2024; Bricheno et al. 2021). These changes can drastically affect salinity distribution in estuaries, as increased freshwater inflow from heavy rainfall can reduce salinity levels, while prolonged dry periods can lead to higher salinity intrusion (Nuryazmeen, 2018; Nuryazmeen et al. 2013; Nuryazmeen & Tahir, 2016). Such fluctuations can disrupt estuarine ecosystems, impacting species that are sensitive to salinity changes, such as fish and shellfish, and compromising water resources used for drinking and irrigation (Hoagland et al. 2020). For instance, recent studies have shown that extreme rainfall events can cause rapid freshening of estuarine waters, leading to habitat loss for marine species (Davis et al. 2022; Dharmarathne et al. 2024; Li et al. 2024; Röthig et al. 2023). Additionally, changes in salinity can alter nutrient cycling and primary productivity, further affecting estuarine biodiversity (Chaudhary & Krishna 2021; Röthig et al. 2023; Thrush et al. 2013; Zhou & Endreny 2020).

Beyond ecological impacts, variations in estuarine salinity also affect socioeconomic activities. Salinity intrusion into freshwater sources can reduce the availability of potable water, impact agricultural irrigation, and degrade industrial water supplies. Regions that rely on estuarine fisheries for food security and livelihoods are particularly vulnerable to these changes, making it imperative to develop adaptive management strategies for estuarine salinity control. Furthermore, increased salinity levels in estuaries can lead to economic losses in sectors such as aquaculture, tourism, and coastal infrastructure development. The rise in salinity due to reduced freshwater inflows can also accelerate corrosion in bridges, piers, and other coastal structures, leading to higher maintenance costs.

The interaction between freshwater inflow and salinity is particularly complex in meandering estuaries, where channel geometry and flow dynamics play a significant role in shaping salinity patterns (Jumain et al. 2022). Meander bends, for example, can create localized areas of higher salinity due to secondary circulation patterns, which are influenced by flow velocity and channel curvature (Martín-Llanes & López-Ruiz, 2024; Park et al. 2020; Pein et al. 2018). These factors make it challenging to predict salinity distribution under varying rainfall conditions, highlighting the need for detailed experimental and numerical studies. Furthermore, estuarine hydrodynamics are influenced by interactions between stratification, turbulence, and sediment transport, all of which require comprehensive analysis to improve predictive models. These processes interact in highly non-linear ways, making it essential to employ both physical and numerical models to gain a holistic understanding of salinity dynamics.

Recent advancements in remote sensing and in-situ monitoring have provided new opportunities for improving salinity modelling and management strategies. The integration of satellite-based salinity data with hydrodynamic models can enhance the accuracy of predictions and enable real-time decision-making. In addition, machine learning approaches have been increasingly applied to estuarine studies, offering data-driven insights into the complex relationships between hydrological and meteorological variables affecting salinity intrusion. However, most of these studies rely heavily on large-scale datasets or straight-channel estuary conditions, while the response of meandering estuaries to variable tropical rainfall remains understudied (Ali et al. 2024; Buathongkhue et al. 2024; Krisnayanti et al. 2024; Park et al. 2020; Xie et al. 2019; Yanfatriani et al. 2024; Zhou & Endreny, 2020). This gap highlights the need for controlled physical experiments coupled with advanced numerical modelling to quantify rainfall impacts more precisely.

This study addresses the gap by quantifying the impact of varying rainfall-induced freshwater flows on salinity dynamics using a combination of laboratory experiments and MIKE 21/3 numerical modelling. Unlike previous works that emphasize remote-sensing validation or straight estuary channels, this research uniquely integrates a meandering flume experiment with three-dimensional simulations. The approach provides a clearer understanding of how channel morphology, rainfall intensity, and freshwater inflows interact to influence salinity intrusion length and distribution.

The laboratory experiments simulate different rainfall scenarios (light, normal, and heavy) in a meandering channel, while the MIKE 21/3 model is used to validate and extend the findings. By focusing on a controlled experimental setup, this study provides a detailed understanding of how changes in freshwater inflow affect salinity intrusion length and concentration. Recent advancements in numerical modelling have demonstrated the effectiveness of MIKE 21/3 in simulating estuarine hydrodynamics and salinity distribution, particularly under varying freshwater inflow conditions (Khalil et al. 2025; Qiao et al. 2018). The integration of experimental and numerical approaches provides a robust framework for assessing estuarine responses to hydrological variability. The combination of these methods allows researchers to account for uncertainties in physical modelling while benefiting from the computational efficiency of numerical simulations.

The scope of this study is limited to a meandering channel model, which replicates key features of natural estuarine systems. The channel is designed to simulate varying freshwater flow rates (Q_{low} = 2.4 L/s, $Q_{moderate}$ = 3.2 L/s, and Q_{heavy} = 4.8 L/s) representing different rainfall intensities. The study analyzes the effects of these flow rates on salinity distribution, with a particular focus on how salinity intrusion length and concentration respond to changes in freshwater inflow. Additionally, the influence of channel morphology, such as bed roughness and curvature, on salinity mixing will be examined. This approach allows for a systematic investigation of the relationship between rainfall patterns and salinity dynamics, providing valuable insights for estuarine management under changing climatic conditions. The study also considers the impact of anthropogenic activities, such as dam construction and land use changes, which can exacerbate the variability of freshwater inflows into estuarine environments.

By developing an enhanced understanding of these processes, this research contributes to the broader field of hydrodynamics and estuarine management. The novelty of this work lies in its integrated experimental–numerical approach, the explicit focus on meandering estuaries under tropical rainfall conditions, and its potential to inform adaptive strategies for estuarine conservation. The findings are expected to offer practical insights into how estuarine systems respond to rainfall variability, facilitating the development of more resilient water resource management strategies. The outcomes of this study will be particularly beneficial for coastal planners, environmental regulators, and water resource managers aiming to mitigate climate change impacts on estuarine environments. By highlighting both scientific contributions and management implications, this work advances theoretical knowledge while offering actionable solutions for sustainable estuarine adaptation.

METHODOLOGY

Understanding estuarine salinity dynamics requires a combination of empirical observations and numerical modelling. The methodology adopted in this study integrates controlled laboratory experiments with computational simulations to analyze the effects of varying freshwater discharge on salinity intrusion. The experimental approach allows for direct observation of physical processes, while numerical modelling extends these findings by simulating additional scenarios that are difficult to replicate in a laboratory setting. This integrated approach ensures a comprehensive assessment of how rainfall-induced freshwater inflow influences estuarine salinity patterns.

EXPERIMENTAL SETUP

A physical model of a meandering estuarine channel was constructed in a hydraulic laboratory to simulate real-world estuarine conditions. The experimental flume measured 10 meters in length, 0.3 meters in width, and 0.6 meters in depth, with a fixed bed slope of 0.00125 and a sinuosity index of 1.09. The channel bed was lined with uniform sand to replicate natural bed roughness, while transparent acrylic walls allowed clear observation of flow dynamics. The experimental model was designed to closely mimic natural estuarine processes while maintaining control over boundary conditions and flow parameters.

Freshwater and saltwater flows were controlled to replicate different rainfall scenarios, categorized as low (2.4 L/s), moderate (3.2 L/s), and heavy (4.8 L/s) discharge rates. The constant downstream discharge of saltwater was maintained at 4.2 L/s. A tailgate mechanism was employed at the downstream end to regulate water levels, ensuring consistency in experimental conditions. Water temperature and density were monitored to ensure minimal variation that could affect salinity mixing patterns. The selection of freshwater discharges (2.4, 3.2, and 4.8 L/s) was based on representing typical low, average, and extreme rainfall-runoff conditions observed in tropical catchments, ensuring that the experimental results reflect realistic hydrological scenarios. The constant saltwater inflow (4.2 L/s) was chosen to maintain a stable saline boundary, which is essential for comparative analysis across cases. Manning's roughness coefficient was adopted within the recommended range for laboratory-scale channels, while sensitivity analyses on Manning's n, turbulent diffusivity, and inflow salinity concentration confirmed that variations in these parameters did not significantly affect the overall salinity intrusion patterns, thereby validating the appropriateness of the selected parameter set.

Salinity measurements were recorded at various depths (0.2 m, 0.4 m, 0.6 m, 0.8 m, and 1.0 m) along the channel. A red dye tracer was used to visualize mixing behavior, while conductivity sensors were positioned at multiple locations to capture real-time salinity variations. The experimental setup allowed for high-resolution monitoring of salinity gradients and mixing processes. Additionally, velocity profiles were measured using an Acoustic Doppler Velocimeter (ADV) to analyze flow structures and turbulence characteristics within the channel.

The experimental setup is summarized in Figure 1 until Figure 3, which illustrates the channel design. The unit in the figures are used in millimeter (mm). Meanwhile, Table 1 shows the details of the geometrical parameters of the experimental channel.

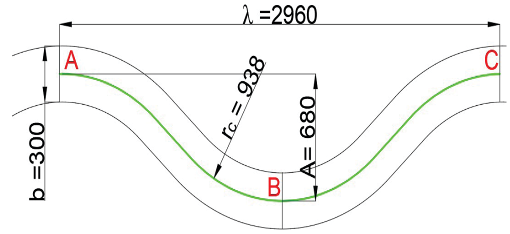

FIGURE 1. Details of Meandering Channel

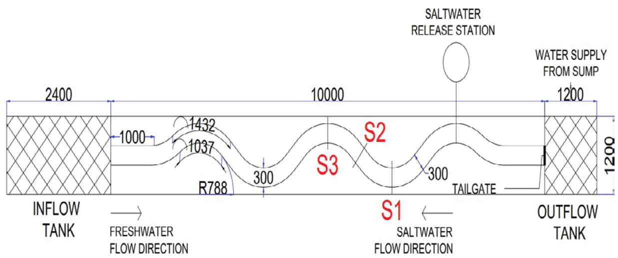

FIGURE 2. Plan View of the Meandering Channel

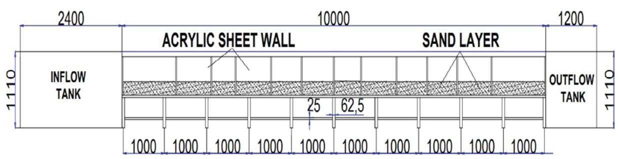

FIGURE 3. Side View of the Meandering Channel

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

Station	Distance from tailgate, *x* (m)
x_1	3.25
x_2	4.26
x_3	5.00

TABLE 2. Location of the sampling based on the y-axis

Station	Distance from channel wall, *y* (m)
y_1	0.28
y_2	0.15
y_3	0.28

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

Station	Distance from channel bed, z (m)
z_1	0.0
z_2	0.2
z_3	0.4
z_4	0.6
z_5	0.8
z_6	1.0

TABLE 4. Details of geometrical parameters of the experimental channel

Item description	Present experimental channel
Types of channel	Meandering channel with fixed wall
Nature of the surface of the bed	Fixed-bed channel with a smooth concrete surface
Flume size (m)	10 (*L*) x 0.3 (*B*) x 0.6 (*H*)
Wavelength of the channel, λ (m)	2.96
Amplitude, *A* (m)	0.68
Channel width, *B* (m)	0.30
Bed slope of the channel, *s*	0.00125
Deflection angle, ω	83º
Bank full depth of the channel, *H* (m)	0.60
Radius of curvature of channel centreline at bend apex, r_c (m)	0.94
Sinuosity ($K=L/\lambda$)	1.09

MIKE 21/3 MODELLING

The MIKE 21/3 hydrodynamic model was employed to simulate three-dimensional salinity distribution and validate the experimental findings. The model incorporated the Reynolds-averaged Navier-Stokes equations and utilized a turbulence closure scheme to account for mixing and dispersion (Qiao et al. 2018). The computational domain was developed to reflect the physical model's bathymetry and boundary conditions, ensuring a direct comparison between experimental and numerical results. The workflow of the MIKE 21/3 modelling process, including mesh generation, boundary condition setup, and calibration, is depicted in Figure 4.

Model calibration was conducted using observed water level and salinity concentration data. An unstructured mesh consisting of 336 elements and 425 nodes was generated to capture detailed flow dynamics, with mesh refinement in high-gradient regions to improve accuracy (Figure 5). Boundary conditions were set based on experimental flow rates, and model simulations were run under steady-state and transient conditions to assess salinity distribution over time. The model's performance was evaluated using statistical metrics such as the coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE), and Root Mean Square Error (RMSE) to ensure reliability.

To enhance the model's predictive capabilities, sensitivity analyses were conducted on key parameters, including Manning's roughness coefficient, n, turbulent diffusivity, and inflow salinity concentration. The calibration process aimed to achieve the best possible agreement between observed and simulated results, refining the model to improve its representation of physical processes. The validated model was then used to extend the experimental findings, exploring additional scenarios such as varying tidal influences and sediment transport effects on salinity dynamics.

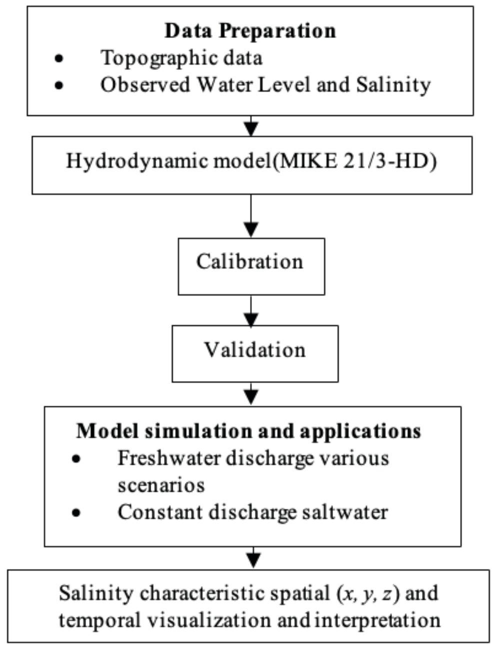

FIGURE 4. Schematic of the Modelling Framework for Numerical Model

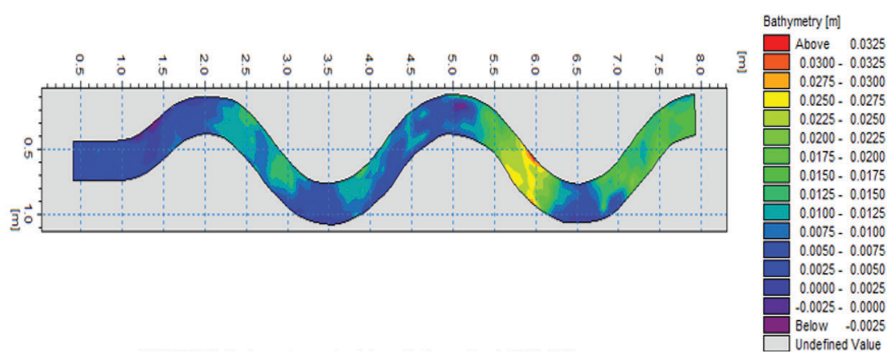

FIGURE 5. Bathymetry and grid resolution using MIKE 21/3

MODEL PERFORMANCE ANALYSIS

To assess the accuracy of the MIKE 21/3 model, statistical validation metrics were applied, including the coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE), and Root Mean Square Error (RMSE). These metrics help evaluate the degree of correlation between observed and simulated values, ensuring that the model accurately replicates physical conditions.

The coefficient of determination (R^2) is used to measure the strength of the relationship between observed and predicted values. It is calculated as follows (Equation 1):

$$R^2 = 1 - \frac{\Sigma(O_i - P_i)^2}{\Sigma(O_i - \bar{O})^2} \tag{1}$$

where O_i is the observed value, P_i is the predicted value, $\bar{O}$ is the mean of observed values. An R^2 value closer to 1 indicates a strong correlation between model predictions and experimental data, signifying high model accuracy.

The Nash-Sutcliffe Efficiency (NSE) is another key performance indicator, which evaluates how well the model predicts compared to the mean of the observed data (Equation 2):

$$NSE = 1 - \frac{\sum(O_i - P_i)^2}{\sum(O_i - \bar{O})^2} \quad (2)$$

where the variables remain the same as defined for R^2. NSE values range from negative infinity to 1, with values above 0.5 considered acceptable for hydrodynamic modelling.

The Root Mean Square Error (RMSE) provides a measure of the average magnitude of the prediction error (Equation 3):

$$RMSE = \sqrt{\frac{1}{n}\sum(O_i - P_i)^2} \quad (3)$$

where n is the number of observations. Lower RMSE values indicate better model performance, as they suggest minimal deviation between observed and predicted values.

Statistical validation metrics were used to quantify the model's performance. R^2 values above 0.7 were considered indicative of strong correlation between observed and simulated values, while NSE values greater than 0.5 were deemed satisfactory for hydrodynamic modelling studies. RMSE values were analyzed to determine the model's precision in predicting salinity variations under different flow conditions.

To further validate the experimental results, uncertainty analysis was conducted, considering measurement errors, sensor calibration accuracy, and environmental factors affecting salinity readings. This approach ensured the robustness of the findings and provided a comprehensive assessment of estuarine salinity dynamics under varying rainfall scenarios.

Data collected from both the physical experiments and numerical simulations were analyzed to evaluate the impact of freshwater discharge on estuarine salinity intrusion. Time-series analysis was conducted to observe temporal fluctuations in salinity, while spatial interpolation methods were employed to map salinity distribution across the channel length and depth. Comparative analysis between experimental and simulated results was performed to assess model accuracy and identify any discrepancies.

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To further validate the experimental results, uncertainty analysis was conducted, considering measurement errors, sensor calibration accuracy, and environmental factors affecting salinity readings. This approach ensured the robustness of the findings and provided a comprehensive assessment of estuarine salinity dynamics under varying rainfall scenarios.

By integrating experimental observations with numerical modelling and rigorous data validation techniques, this study aims to enhance the understanding of estuarine salinity responses to hydrological variability. The combined approach provides a reliable framework for predicting and managing estuarine salinity changes, contributing to improved coastal water resource management strategies.

RESULTS AND DISCUSSION

The results of this study provide a comprehensive analysis of how variations in freshwater discharge influence salinity dynamics in a meandering estuarine channel. By integrating laboratory experiments with numerical modelling, this study examines the spatial and temporal distribution of salinity, the effectiveness of the MIKE 21/3 model, and the implications for estuarine management. The findings highlight the significant role of freshwater discharge in controlling salinity intrusion length and stratification, which are crucial for maintaining ecological balance in estuarine environments.

A detailed evaluation of model performance is presented, followed by discussions on the impact of varying freshwater inflows on salinity distribution. The study also investigates the spatial and temporal variations in salinity levels and explores management strategies to mitigate salinity intrusion. The combination of experimental and numerical approaches offers a robust framework for understanding estuarine hydrodynamics and provides valuable insights for future studies and water resource management strategies.

MODEL PERFORMANCE

The calibration process for the MIKE 21/3 model began with adjustments to the hydrodynamic parameters, followed by validation of water level and salinity concentrations. The primary focus was on fine-tuning key parameters, such as the Manning coefficient, n, to ensure that the numerical model accurately represented the physical conditions observed in the laboratory experiments.

The Manning coefficient, *n* was adjusted to achieve consistent flow conditions across the entire domain without altering the experimental setup. The calibration results, specifically under Case 1-Q_{low}, as illustrated in Figure 6, showed that Manning's *n* values adhered to a 30% variation limit, indicating a stable and reliable calibration process.

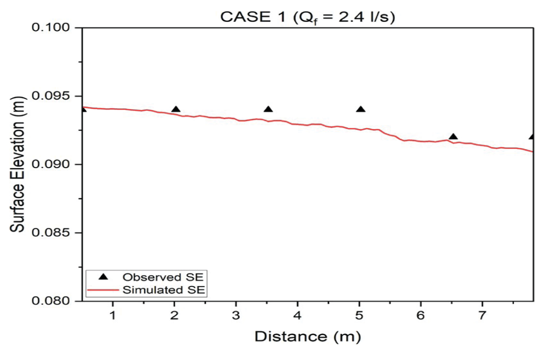

FIGURE 6. Calibration of Water Level under Case 1- Q_{low}

To validate the model, observed water levels from the central cross-section of the meandering channel were compared with simulated water levels. The calibration process yielded model outputs that closely matched the measured data, as depicted in Table 5. The coefficient of determination (R^2) values for different cases were consistently above 0.7, demonstrating a strong correlation between observed and simulated water levels. This high level of accuracy in simulating streamflow is crucial for the reliable prediction of salinity intrusion, as highlighted in previous studies (Bihon et al. 2024).

TABLE 5. Model Validation of Water Level

Water Level (m)	Case 1 - Q_{low}
Calibrated Manning's *n*	0.036
R^2	0.767
RMSE	0.089

The validation of salinity intrusion was conducted by comparing observed and simulated salinity profiles at various sections of the channel (Figure 7). The results, summarized in Table 6, showed that the model performed well across different freshwater discharge scenarios. For Case 1-Q_{low}, the R^2 values ranged from 0.91 to 1.00, with NSE values indicating "Good" to "Satisfactory" performance.

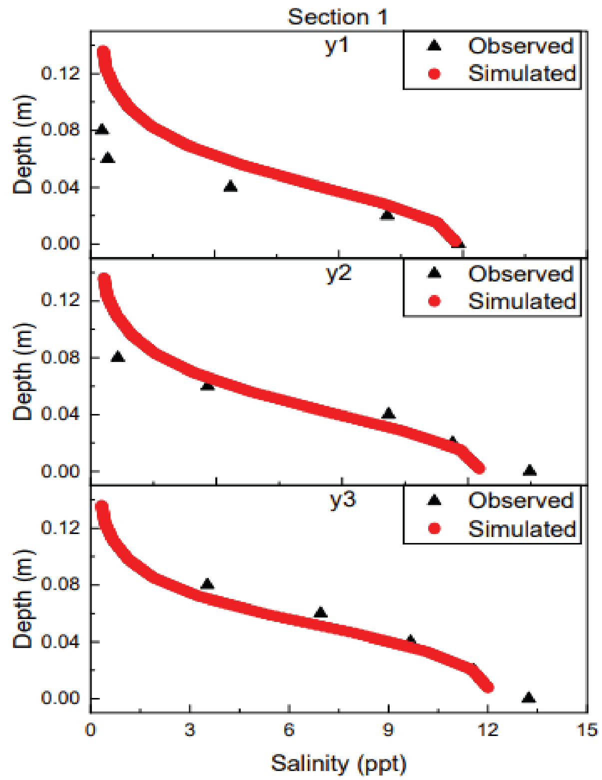

FIGURE 7. Validation of Salinity Concentration under Case 1-Q_{low}

The validation process revealed that the model accurately captured the spatial and temporal variations in salinity, particularly in the downstream sections of the channel. However, some discrepancies were observed in the upstream sections, where the model slightly underestimated salinity levels. These discrepancies were attributed to the complex interactions between freshwater flow and saltwater intrusion, particularly in the meandering bends of the channel, where secondary circulation patterns can significantly influence salinity distribution.

EFFECT OF FRESHWATER DISCHARGE ON SALINITY INTRUSION LENGTH

The study also examined the impact of varying freshwater discharge rates on the length of salinity intrusion from the estuary mouth. As expected, higher freshwater discharge rates (Case 3-Q_{heavy} = 4.8 L/s) resulted in a significant reduction in salinity intrusion length, as the increased freshwater flow restricted the upstream progression of saltwater, as illustrated in Figure 8 and summarized in Table 7.

TABLE 6. Model Performance in the Validation of Salinity Intrusion for Case 1

Section	*y*-axis	R^2	NSE	Interpretation
1	y_1	0.93	0.51	Satisfactory
	y_2	0.97	0.92	Good
	y_3	0.98	0.88	Good
2	y_1	0.98	0.92	Good
	y_2	1.00	0.94	Good
	y_3	0.91	0.53	Satisfactory
3	y_1	0.99	0.67	Satisfactory
	y_2	0.98	0.73	Satisfactory
	y_3	0.98	0.56	Satisfactory

Conversely, lower freshwater discharge rates (Case 1-Q_{low} = 2.4 L/s and Case 2-$Q_{moderate}$ = 3.2 L/s) allowed saltwater to intrude farther upstream, particularly at the bottom and mid-depth sections of the channel. This pattern aligns with real-world observations in estuarine systems, where reduced freshwater flow can lead to increased salinity intrusion, especially during periods of low rainfall.

The findings underscore the importance of channel geometry and flow dynamics in shaping salinity patterns. The meandering nature of the channel, with its bends and secondary circulation, played a crucial role in influencing the lateral and vertical distribution of salinity. These results highlight the need for accurate modeling of channel geometry and flow conditions when predicting salinity intrusion in estuarine environments.

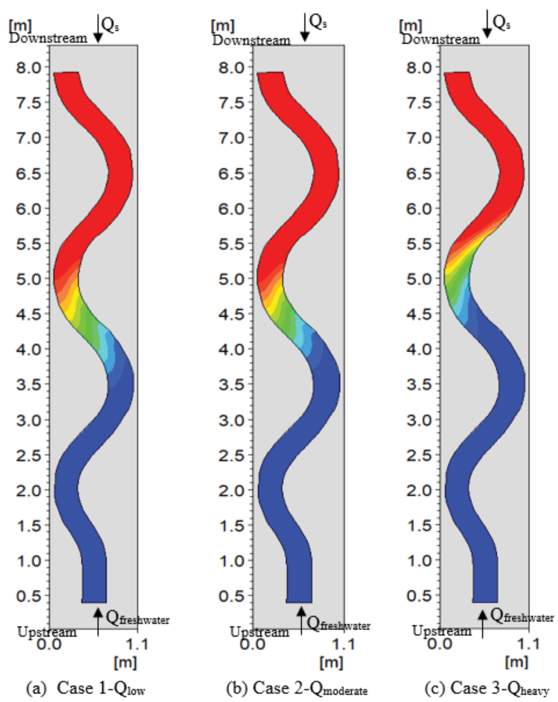

FIGURE 8. Differences in the Maximum Salinity Intrusion Length along the Meandering Channel for (a) Case 1-Q_{low}, (b) Case 2-$Q_{moderate}$, and (c) Case 3-Qh_{eavy}

TABLE 7. Spatial Distribution of Salinity Intrusion Length

Case	1	2	3
Condition	Q_{low}	$Q_{moderate}$	Q_{heavy}
Upstream Discharge (L/s)	2.4	3.2	4.8
Downstream Discharge (L/s)	4.2	4.2	4.2
Distance from the Downstream (m)	5.0	4.8	3.5

CONCLUSION AND RECOMMENDATION

In conclusion, the MIKE 21/3 model demonstrated strong performance in simulating both hydrodynamic and salinity dynamics in a meandering channel under varying freshwater discharge conditions. The calibration and validation processes confirmed the model's ability to accurately predict water levels and salinity intrusion, with R^2 and *NSE* values consistently meeting or exceeding acceptable thresholds. The study also highlighted the significant impact of freshwater discharge on salinity intrusion length, emphasizing the need for careful consideration of flow dynamics and channel geometry in estuarine management and modeling efforts. Unlike previous studies that focused mainly on straight estuaries or remote-sensing analysis, this research provides a novel contribution by integrating controlled flume experiments with three-dimensional modelling in a meandering estuary context, thereby addressing a critical research gap in tropical rainfall–salinity interactions. The integration of physical modeling and numerical simulations provided a comprehensive understanding of how changes in freshwater inflow influence salinity distribution, highlighting the complex interplay between hydrodynamic forces and estuarine morphology. This work not only validates the effectiveness of MIKE 21/3 as a predictive tool but also advances theoretical understanding of the role of meander geometry and rainfall variability in shaping salinity dynamics.

Nevertheless, some limitations should be acknowledged. The present study did not incorporate tidal interactions, sediment transport, or wind forcing, all of which are important drivers of salinity distribution in natural estuaries. Furthermore, the physical model adopted certain simplifications, which, although necessary for controlled experimentation, may not fully represent the complexity of real-world boundary conditions. These limitations highlight the importance of extending the research beyond laboratory conditions to strengthen its applicability to actual estuarine environments.

Building upon these findings, future research should expand by investigating the role of tidal dynamics, sediment transport, and wind effects, as well as the influence of anthropogenic activities such as dam construction and land-use change. The integration of machine learning techniques with hydrodynamic modelling is also recommended, as it could enhance predictive capabilities and allow for adaptive management under increasingly unpredictable climate conditions. Additional experimental studies using diverse estuarine geometries would provide deeper insights into the influence of channel morphology on salinity mixing. Finally, this research underscores the need for interdisciplinary collaborations between engineers, environmental scientists, and policy-makers, thereby motivating the development of actionable and holistic strategies for estuarine conservation and sustainable water resource management.

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DECLARATION OF COMPETING INTEREST

None.

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