Mechanism of sanility intrusion and temporal distribution of freshwater in the Dinh An estuary, Vietnamese Mekong delta

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Abstract: The Vietnamese Mekong Delta (VMD), responsible for over half of Vietnam's rice production and most of its aquaculture and fruit yields, is facing freshwater shortages due to intensified salinity intrusion (SI) and climate change impacts. This study integrates field measurements and MIKE 3D numerical modelling to analyze the spatial and temporal dynamics of salinity intrusion in the Dinh An branch of the Hau River. Results show that peak salinity concentration (S_{max}) typically occurs near the bottom, lagging 1–2 hours behind maximum water level during tidal cycles and 4-6 days in fortnightly tidal cycle during the neap–spring transition. The Dinh An estuary exhibits partial mixing with moderate stratification, with freshwater availability extending approximately 30 km inland during the dry season. The research results provide an important scientific basis for optimizing sluice gate operations to manage freshwater intake.

Keywords: Salinity intrusion, Mekong estuaries, tidal regime, mixing and stratification.

I. Introduction

The Mekong River (MR), one of the world's major transboundary rivers, extends approximately 4,800 km from the Tibetan Plateau to the South China Sea, draining a basin of about 795,000 km². Within Vietnam, the river divides into two principal branches-the Tien and Hau Rivers-that form the Vietnamese Mekong Delta (VMD). Around 85% of the total flow initially passes through the Tien River and is later redistributed to the Hau River via the Vam Nao channel. The Hau River, which contributes about 42% of the total freshwater discharge (Nguyen et al., 2009), is divided into the Dinh An and Tran De distributaries at Cu Lao Dung Island before reaching the East Sea (Fig.1).

The VMD plays a crucial role in national food security, providing over 50% of Vietnam's rice and 70% of aquaculture production (Salinity report, 2024). However, it is increasingly threatened by hydrological alterations, land subsidence, coastal erosion, drought, and climate change. Among these, salinity intrusion (SI) has become a critical challenge, affecting agriculture, domestic water supply, and ecosystems. Over the past decade, saline intrusion has occurred 1–1.5 months earlier and lasted about 1.5 times longer than historical averages, with peak salinity now arriving up to two months earlier. (Mai, 2022 and Salinity report, 2024).

Salinity intrusion (SI) is a dynamic estuarine process arising from the interaction between freshwater and seawater under tidal and hydrological forcing. Following the conceptual framework of Savenije (2012), SI occurs when tidal energy drives seawater landward while reduced upstream discharge weakens the river's flushing capacity. The extent of intrusion is governed not only by river flow but also by tidal amplitude, channel geometry, bathymetry, friction, and vertical mixing conditions, often producing partially mixed or stratified estuaries in which bottom salinity penetrates substantially farther inland than surface salinity. In the Mekong system, a decline in upstream discharge-exacerbated by the construction of more than 128 reservoirs-has altered the seasonal flow regime and modified tidal propagation patterns (Mai et al., 2018). Although some studies reported increased dry-season discharge at upstream stations such as Chiang Saen and Kratie (Kuenzer et al., 2013) (Räsänen et al., 2012), salinity intrusion in the delta continues to intensify, underscoring the dominant role of tidal dynamics and estuarine morphology in controlling intrusion length.

Several studies have analyzed tidal amplification (Eslami et al., 2019) or mapped spatial salinity distributions (Gugliotta et al., 2017; Marcello et al., 2017), yet most remain limited in depth-dependent salinity observations so the mixing and stratification at Mekong estuaries has not been comprehensively quantified. These limitations highlight the need for long-term, vertically resolved analyses to better understand SI mechanisms and their implications for freshwater availability in the Vietnamese Mekong Delta.

Similar patterns have been reported in other large deltas such as the Mississippi, Chao Phraya, and Pearl River, where maximum salinity (S_{max}) often occurs during the transition from neap to spring tides (Gong & Shen, 2011). In the VMD, Mai (2022) observed that intrusion length can vary by 6–15 km between low and high tides and that peak salinity typically precedes the spring tide by several days. In the Hau River, bottom salinity intrusion lengths are consistently 6–20 km greater than surface values, implying that freshwater with salinity below 1 psu (practical salinity unit) may

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Received 13th Nov. 2025
Accepted 16th Dec. 2025
Publication date 31st Dec. 2025

still be available up to 35 km from the estuary during dry-season ebb tides.

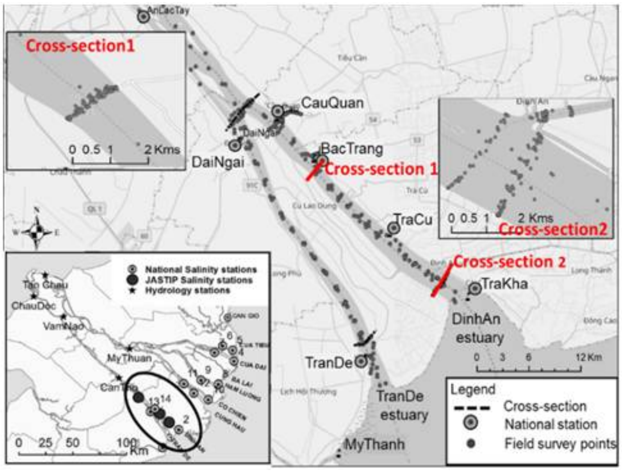

Fig 1. Location map of Study Area

Despite substantial progress, significant uncertainties remain regarding the vertical and longitudinal distribution of salinity and its temporal variability under tidal forcing. This study aims to quantify the spatial and temporal differences in salinity concentration (S) and intrusion length (L) between surface and bottom layers along the Dinh An branch. The results provide insights into the mechanism of SI and freshwater occurrence timing and support the efficient operation of sluice gates for water intake during the dry season.

2. Data and methodology

Building upon previous national and international research, and answers the question what kind of mixing and stratification will appear at the Mekong estuarine, the research team employed a combined methodological approach. Three measurement techniques were applied during a three-day field survey on the Hau River, complemented by experimental procedures to verify the presence of stratification. Subsequently, a three-dimensional (3D) numerical model was applied to simulate long-term tidal conditions, using field observations for model calibration and validation.

2.1. Data collection

The datasets used for setup MIKE3D model and calibration include: Can Tho discharge (QCT) and hourly water level and salinity observations at Dai Ngai and My Thanh (WL) from November 2015 to May 2016, provided by the Southern Southern Regional Hydro-Meteorological Center (SRHMC). Field measurements of salinity were collected along 16 and 18 vertical profiles on the Dinh An and Tran De branches, respectively, on 31 March and 1 April 2016. Bathymetric data covering the area from the downstream of Cu Lao Dung island to 20 km offshore (2018) were obtained from the Southern Institute for Water Resources Research (SIWRR), supplemented by bathymetric measurements conducted by the research team on the Hau River in August 2017 (Mai, 2022)

2.2. Field survey

Field survey: Two field campaigns were undertaken during spring tides in 2018 and 2019. The first, on 4 March 2018, involved vertical and longitudinal salinity profiling along 45km of the Dinh An and TranDe branch from the river mouth during both ebb and flood tides by using CastAway-CTD, YSI ProDSS, and Infinity-ACTW instruments. The second campaign (22-23 April 2019) measured vertical salinity and velocity profiles at two cross-sections: one 22 km and another 3 km from the estuary. Data were acquired hourly over 12-hour tidal cycles using Acoustic Doppler Current Profiler (ADCP) and CTD CastAway equipment.

2.3. Mixing and Stratification Classification

There are three types of vertical mixing and stratification of water revealed in the zone of river and sea water mixing: type I is complete mixing and weak stratification; type II is partial mixing and moderate stratification; type III is weak mixing and strong stratification, saltwater wedge (Marcello et al., 2017). Stratification parameter n (Pritchard's number) is used for such classification and is calculated as:

$$n = \frac{\Delta S}{S_m} = \frac{S_{bot} - S_{surf}}{0.5(S_{bot} + S_{surf})} \quad [1]$$

where ΔS is the vertical gradient of water salinity, S_m is depth averaged water salinity, S_{bot} and S_{surf} are saline water at the bottom and on the surface, respectively.

The ranges of n are shown in Table 1.

Table 1. Quantitative criteria of different types of salinity stratification

Type of Seawater intrusion	Character of vertical mixing	Character of stratification	Pritchard n
I	Well mixing	Weak	0 ÷ 0.1
II	Partial mixing	Moderate	0.1 ÷ 1.0
III	Weak mixing	Salt Wedge	> 1.0

2.4. Numerical Modelling

MIKE 3 FM-AD was applied over a 110 km stretch from Can Tho to the estuaries. The unstructured mesh comprised rectangular (200 × 80 m) and triangular (5,000–30,000 m²) elements. Boundary conditions included measured upstream discharges at CanTho, predicted tidal levels by Tide prediction in MIKE 21, and an offshore salinity of 32 psu (practical salinity unit). Model calibration used observed water levels from two stations, Tran De (T1) (after 2016), Dai Ngai (T2) collected by the SRHMC and observed salinity data at T1, T2, D1, D2, H1, H2 points (Fig.2) on 1 April 2016 by SIWRR.

Figure 3 and Figure 4 present the calibration results for water level and salinity concentration. The water level calibration shows relatively good accuracy, with R^2 ranging from 0.81 to 0.95. Meanwhile, the salinity correlation at the validation points varies by location, with R^2 values between 0.77 and 0.83 (Hai, 2022) as the measured salinity is strongly influenced by the timing of the measurement and the flow velocity at the moment the instrument is deployed. Nevertheless, the overall trend and vertical salinity profile remain consistent, with salinity decreasing gradually with increasing water depth.

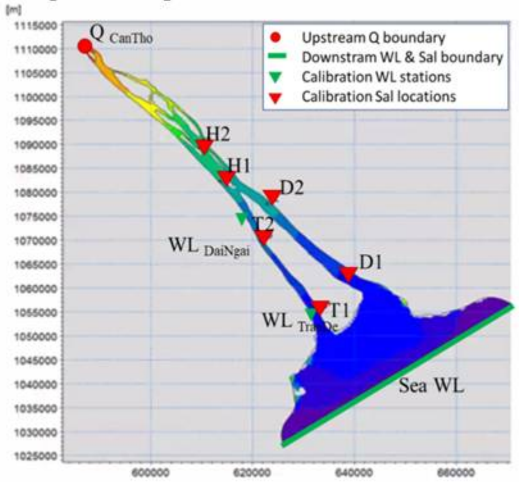

Fig 2. Model setup

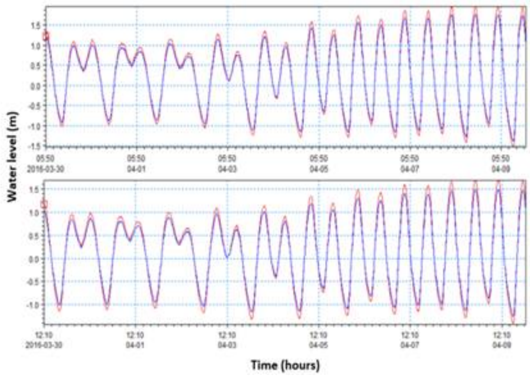

Fig 3. Water level calibration at T1 (TranDe - 5km) station and T2 (DaiNgai - 30km)

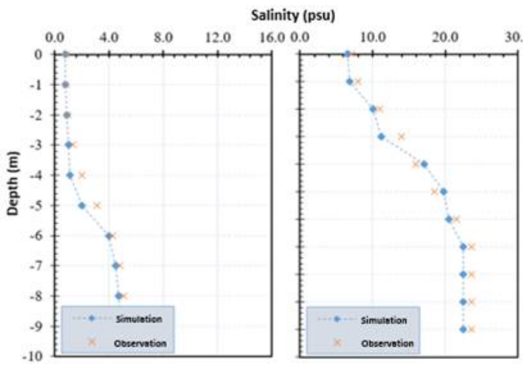

Fig 4. Salinity calibration at T2 (2:00pm) (DaiNgai - 30km) and T1(5:20pm) (TranDe - 5km) station on 1 April 2016

3. Results and discussion

3.1. Salinity distribution during 1 tidal cycle

Field observations on 4 March 2018 indicated that S_{max} increased progressively downstream during ebb tide, peaking at 8.92 psu near the river mouth. During flood tide, salinity intrusion of 0.5 psu or 1 psu extended 15 km further inland than during ebb tide (Fig. 5). Stratification analysis revealed partial mixing ($0.1 < n < 0.7$), with notable vertical salinity gradients between 10–25 km from the estuary. Furthermore, a significant difference in salinity concentration between the surface and bottom occurs at the estuary in the flood tide, whereas this difference appears between the 10 km and 45 km points during ebb tide.

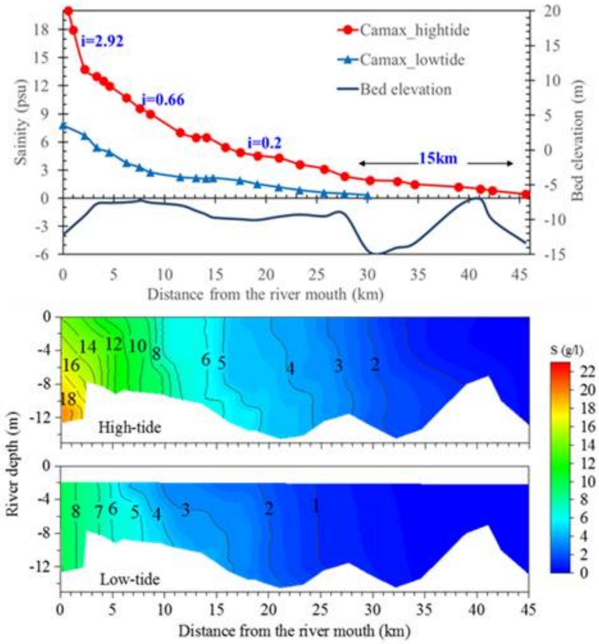

Fig 5. Vertical and longitudinal distribution of saltwater in the DinhAn branch

Hourly data at the cross-section 1 far from the river mouth, 22km, were conducted during 12 12-hour period from 9:15 to 21:00. During the ebb tide from 9:15 to 13:00, salinity concentrations decreased from 0.89 psu to 0.14 psu. The minimum salinity value of 0.14 psu occurred at 13:00, coinciding with the lowest water level of -0.97 meters (Fig.6). Subsequently, the water level rose from -0.97 m to reach a maximum level (WL_{max}) of 1.67 m at 18:00, leading to salinity concentrations increasing from 0.14 psu to 1.69 psu. S_{max} in the surface of 1.04 psu occurred at 18:00 (Fig.6) while S_{max} at the bottom of 1.74 psu appeared at 19:00.

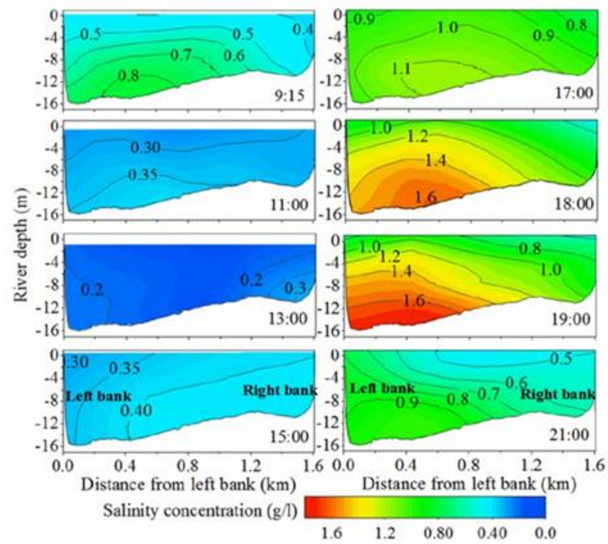

Fig 6. The vertical distribution of salinity concentration at cross-section 1 during a tidal cycle

That means while surface S_{max} coincided with WL_{max}, bottom S_{max} lagged one hour behind WL_{max} at a location of 22 km far from the river mouth (cross-section 1) (Fig.1). Fig.6 also showed that salinity profiles displayed clear lateral heterogeneity. The left bank exhibited faster salinity decrease during ebb tide, reflecting stronger seaward flow, whereas flood tide favored higher salinity accumulation along the right bank. Near-bank where most sluice gates are located got salinity value always lower than mid-channel however stratification remain valuable for sluice operational guidance.

3.2. Salinity distribution during the fortnightly tidal cycle

Three periods have been considered to analysis the mechanism of salinity intrusion in the Neap-Spring tidal scale (from 1 February 2016 to 12 February 2016) (Fig.7). The first period is neap time (1 February 2016), second is the transition from the neap tide to the spring tide (8 February 2016) and the last is the spring tide (11 February 2016). The results showed the most important thing is that the maximum salinity concentration S_{max} appears before the maximum water level in spring tide by 4 to 6 days in Dinh An branch, depending on the time and location. This phenomenon is caused by the interplay between neap tide and high tide events (Fig.7). In the neap tide, the tidal range is reduced, which means that fresh water from the upstream areas does not have enough time to push the salt towards the river mouth during the ebb tide. Consequently, when the high tide arrives sooner, it brings more salt into the river. The salt concentration stored in the river meets the new amount of salinity, leading to salinity accumulation. Conversely, as spring tide approaches, the tidal range is high, causing trough tide to be very low. During this time, the tide is longer, making it easier to dilute or flush out the salt. As a result, the salinity gradually decreases during this period.

The MIKE 3D model results show a trend consistent with the field measurements. Both the maximum salinity concentration and the greatest salinity intrusion length occur during the transition from neap to spring tide, as shown in Fig. 8. Although the intrusion length during spring tide is also considerable, its value is only slightly lower than the maximum intrusion length (L_{max}). Furthermore, Figure 8 illustrates the variation in bottom-layer saltwater intrusion length for a salinity concentration of 1 psu.

During spring tide and the transition period (from neap to spring tide), the intrusion length increased slightly, ranging from 53.5 km to 55 km. In contrast, during neap tide, the intrusion length (L) reached only 38.5 km. That is, the intrusion length at the bottom (L_{bot}) at spring tide or the transition period is 15 km to 17 km longer than that of the neap tide period. Meanwhile, the L_{suf} on the surface with the same concentration of 1 psu is about 5 km to 15 km shorter at low tide and high tide respectively. The L_{min} occurs during the neap tide period, allowing freshwater to appear within the range of 38.5 km to 55 km from the estuary even during the peak salinity period of 2016. This implies that 55 km upstream of Hau River always has fresh water both on the bottom and on the surface during dry season. The operation procedure of tidal sluice gates along 55 km of Mekong tributaries is usually closed during peak salinity of at least 2-3 months in the dry season. Therefore, analyzing the salinity distribution by depth provides valuable information for determining the optimal time to open the sluice gates and access freshwater during dry season months with high salinity levels.

Besides, the ideal salinity level for shrimp farming is approximately 16 psu. This threshold is typically found within the 5 km to 25.5 km range from the estuary. The L_{max} and L_{min} of the 16 psu threshold occur during the transition period and the spring tide phase, respectively. During the spring tide, L was relatively large, but the salinity concentration was much lower than the S_{max} during the transition tide period.

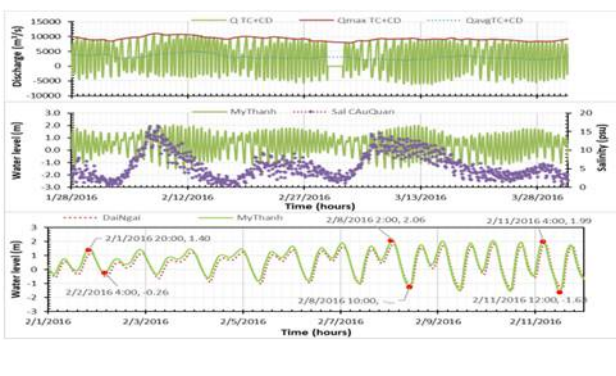

Fig 7. Three time periods for considering the mechanism of salinity intrusion in the monthly tidal scale

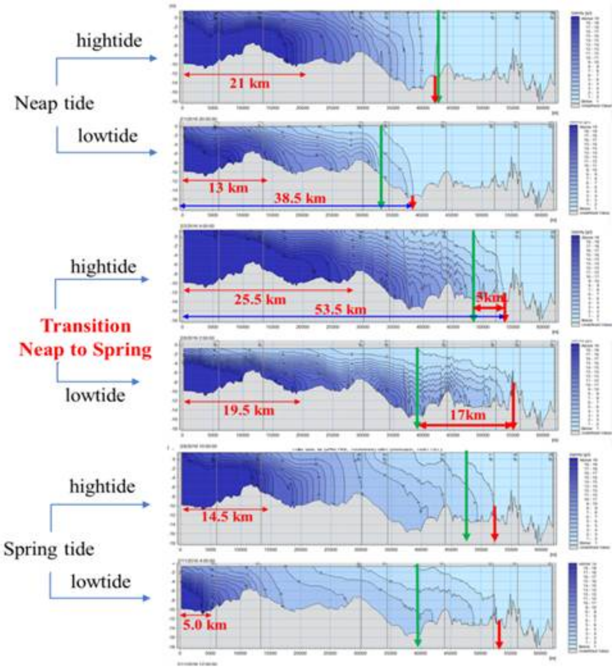

Fig 8. Vertical and longitudinal salinity distribution along DinhAn branch in three time periods in the monthly tidal scale

4. Conclusions and recomendations

The findings of present study demonstrate the significant influence of tidal flow on salinity distribution. In particularly, the intrusion length during ebb tide is 15km shorter compared to flood tide. Longitudinal salinity distribution along the Hau River indicates the partial mixing and moderate stratification condition with Pritchard's number, n = 0.11÷0.68.

Vertical salinity distribution within a cross-section is complicated. S_{min} typically occurs at the surface, while S_{max} is found at the deepest point. This bottom S_{max} can be significantly higher than surface and near-bank values, ranging from 2 g/L to 8.58 g/L. Furthermore, surface S_{max} coincided with the Wl_{max}, whereas bottom S_{max} lags behind WL_{max} by approximately one hour.

During fortnightly tidal cycle, bottom S_{max} occurs at the transition period from neap to spring tides (4-6 days before spring tide). Meanwhile, S_{min} appears at the transition period from spring to neap tides. The intrusion length during the spring tide and transition period is quite similar and longer than that in the neap tide by 15 -17 km.

The Pritchard's number values during the February 2016 range from 0 to 0.68, which means the partial mixing and moderate stratification prevail for DinhAn branch during that time. The mixing and stratification in DinhAn need to be verified by other parameter such as Simmon's number, Richardson's number, etc.

Analyzing the variations in vertical salinity distribution within a single tidal cycle suggests that sluice gates can potentially remain open for at least eight hours during the dry season to access freshwater with a salinity concentration of 1 psu. This research, therefore, provides valuable insights for operating sluice gates along the left bank of the DinhAn branch. Further studies should extend this approach to the remaining six estuaries of the Vietnamese Mekong Delta in order to develop an integrated planning framework or an operational management protocol for sluice systems in stratified estuarine regions.

Acknowledgement

This research is funded by Thuyloi University and Japan-ASEAN Science, Technology and Innovation Platform (JASTIP) and the Supporting Program for Interaction-Based Initiative Team Studies SPIRITS 2016 of Kyoto University

References

Eslami S., Hoekstra P., Trung N.N., Kantoush S.A., Binh D.V., Dung D.D., Quang T.T. and Vegt M.V.D. (2019). *Tidal amplification and salt intrusion in the Mekong Delta driven by anthropogenic sediment starvation.* Scientific Reports, 9.

Gugliotta, M., Saito, Y., Nguyen, V.L., Ta, T.K.O., Nakashima, R., Tamura, T., Uehara, K., Katsuki, K., Yamamoto, S. (2017). *Process regime, salinity, morphological, and sedimentary trends along the fluvial to marine transition zone of the mixed-energy Mekong River delta, Vietnam.* Cont. Shelf Res. 147, 7–26. doi:10.1016/j.csr.2017.03.001.

Gong,W. and Shen,J. (2011). *Response of salt intrusion to changing river flow and tidal amplitude during winter season in the Modaomen Estuary,* Pearl River Delta area, China. Continental Shelf Research 31, 769–788

Hai D. D. (2022). *Study of salinity intrusion mechanisms and proposal of some solutions for rational water exploitation in the estuary and coastal areas of the Vietnam Mekong Delta.* PhD thesis, SIWRR, Vietnam.

Kuenzer, C., Campbell,I., Roch,M., Leinenkugel,P., Tuan,V.Q., and Dech,S. (2013). *Understanding the impact of hydropower development in the context of upstream-downstream relations in Mekong river basin,* Sustainability Science, Vol.8, pp.565-584.

Marcello G., Yoshiki S., Lap N.V., Oanh T.T. K, ReiN, Toru T., Katsuto U. and Seiichiro Y.(2017). *Process regime, salinity, morphological, and sedimentary trends along the aluvial to marine transition zone of the mixed-energy Mekong River Delta, Vietnam, Continental Shelf Research.*

Mai N.P., Kantoush S., Sumi T.S., Thang T.D., Binh D.V., and Trung L.V. (2018). *Assessing and adapting the impacts of dams operation and sea level rising on saltwater intrusions into the Vietnamese Mekong Delta,* Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Eng.) Vol. 74, No. 5, pp. 373-378.

Mai N.T.P. (2022). *Study on Assessment and Adaptation to Saltwater Intrusion under the Impacts of Tide, Sea-Level Rise, Flow and Morphological Changes in the Vietnamese Mekong Delta.* PhD Thesis, Kyoto University, Japan.

Nguyen A. D., Savenije H., Pham D. and Tang D. (2009). *Using salt intrusion measurements to determine the freshwater discharge distribution over the branches of a multi-channel estuary: the Mekong Delta case,* Estuar. Coast. Shelf Sci. 77, 433–445.

Rasanen, T.A., Koponen, J., Lauri, H. and Kummu, M.(2012). *Downstream hydrological impacts of hydropower development in the upper Mekong Basin,* Water Resources Management, Vol. 26, pp. 3495–3513.

Savenije, H.H.G., 2012. *Salinity and Tides in Alluvial Estuaries, Amsterdam: Elsevier, Second Edition.*

Salinity report (2024). *Investigation, Forecasting, and Monitoring of Salinity Intrusion in the Mekong Delta to Support Agricultural Production* Management. SIWRR. http://www.siwrr.org.vn/?gid=93