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Hydrodynamic Impacts of Tributary Sluice Gate Operations on Salinity Intrusion in the Tien River, Vietnamese Mekong Delta

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ABSTRACT

Salinity intrusion and drought pose an escalating threat to freshwater resources in the Tien River, a primary distributary of the Vietnamese Mekong Delta. Sluice gates on its branch channels are widely implemented to counteract this threat by preventing saltwater intrusion and storing freshwater in inland areas; however, their comprehensive impacts on main-river salinity remain inadequately understood. This research utilized a calibrated MIKE 11 hydrodynamic-salinity model to assess how different sluice gate operational scenarios influence the salinity intrusion pattern. Findings demonstrate that closing all tributary sluices (a maximum intervention scenario) results in a landward extension of the 4 g/L salinity isohaline by up to 2.09 km, with localized salinity increases of up to 12.6% at 40 km from the river mouth, diminishing freshwater availability. Scenario analyses revealed that closing sluices near the estuary, especially on high-discharge tributaries, precipitates the most significant adverse effects. In contrast, operating sluices in upper or middle reaches, or on low-flow tributaries, exerted minimal influence. These results highlight that uncoordinated sluice operations can unintentionally worsen salinity intrusion, compounding pressures from sea-level rise, upstream flow decline, and riverbed degradation. Consequently, strategic, spatially aware planning and adaptive management

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of sluice infrastructure are imperative for ensuring freshwater security in the Vietnamese Mekong Delta.

1. INTRODUCTION

The Vietnamese Mekong Delta (VMD) is a region of global agricultural significance, responsible for over 90% of Vietnam's rice exports and sustaining the livelihoods of approximately 65% of its rural populace (General Statistics Office of Vietnam 2021; Lee and Dang 2018). Despite this agricultural prowess, the VMD's productivity and water resource sustainability are increasingly jeopardized, particularly by recurrent severe droughts (Lee and Dang 2018) and pervasive salinity intrusion (SI) during the dry season (Loc et al. 2021; Lee and Dang 2018; Thach et al. 2023). SI, characterized by the landward encroachment of saline water into freshwater systems, critically compromises water quality for domestic, agricultural applications, thereby undermining food security and economic stability in the region (Hak et al. 2016; Smajgl et al. 2015; Takagi et al. 2016).

The principal drivers of SI in the VMD are multifaceted and complex. Natural phenomena, such as strong tidal propagation and sea-level rise (SLR), contribute significantly. However, these natural drivers are substantially exacerbated by extensive anthropogenic alterations. Two dominant factors are reduced freshwater flows from upstream and accelerated local SLR. Upstream hydropower dam construction in the broader Mekong Basin has altered flow regimes, significantly reducing dry-season discharge and sediment loads (Van Binh et al. 2020; Li et al. 2017). This sediment starvation diminishes the delta's accretion capacity and leads to widespread in-channel sand mining, causing riverbed degradation and incision (Eslami et al. 2019; Park 2024). Furthermore, the VMD experiences a rapid rate of relative SLR, a combination of eustatic SLR and significant land subsidence driven by groundwater extraction (Minderhoud et al. 2017), which profoundly alters hydrodynamic regimes and facilitates saltwater penetration.

Numerous studies have documented the escalating threat of SI in the VMD. For instance, Anh et al. (2018), utilizing MIKE 11/21 modeling, projected a 4.9 km advancement of the 4 g/L salinity front in the Hau River by 2036–2065, primarily attributed to climate change and SLR. Eslami et al. (2021), employing a Delft3D model that integrated field observations with coastal-inland dynamics, demonstrated that typhoon-induced SLR could extend SI fronts by an additional 10 km, while riverbed degradation (2008–2018) contributed an extra 5–10 km to SI extension in the Ham Luong River. Further projections, considering the combined impacts of reduced upstream flow and SLR, suggest potential inland shifts of the 4 g/L isohaline by 2–28 km (Vu et al. 2024). Modeling by Duc Tran et al. (2024) also indicates an earlier onset of SI in the dry season, thereby intensifying water scarcity. Beyond these climatic and hydrological factors, upstream dam construction and extensive sand mining have been consistently identified as critical factors aggravating SI in both the Tien and Hau Rivers (Jordan et al. 2019; Ngoc Anh et al. 2022; Park 2024). In response to these pressing challenges, Vietnam has implemented various water resource management strategies, most notably the construction of numerous sluice gates across tributary rivers and canals. These structures are primarily intended to manage freshwater resources and prevent saltwater ingress (Tuoi Tre News 2020). Significant infrastructure projects include the large-scale Cai Lon-Cai Be and Ba Lai sluices, alongside numerous other structures such as the Bong Bot, Tan Dinh, and Vung Liem gates (Tuoi Tre News 2020).

More recently, new sluices have been constructed along the left bank of the Tien River to protect agricultural zones, including the Xoai Hot gate (completed in 2018) and the Nguyen Tan Thanh gate (expected completion in 2025, according to Sai Gon Giai Phong News (2025)). While these sluices have demonstrated localized effectiveness in preserving in-field freshwater, especially during dry periods (Loc et al. 2021), substantial concerns persist regarding their broader, potentially adverse, impacts on the main river system. If not strategically planned and operated, such hydraulic structures may disrupt natural flow regimes and inadvertently intensify SI within the main river channels (Tuan et al. 2007; Thach et al. 2023). Van Binh et al. (2020) observed that an increasing number of sluices might contribute to extending the inland reach of salinity, although their study acknowledged the confounding influence of hydrological variations in drought years. Given Vietnam's current policy direction, which encourages further sluice construction along the Tien River and the expansion of canal storage capacity in the Plain of Reeds (Dinh and Dang 2022; Prime Minister 2012), there is a critical and urgent need for focused research. Specifically, comprehensive studies are required to isolate and quantify the precise effects of sluice gate infrastructure—considering their specific locations (Tuan et al. 2007; Loc et al. 2021).

Therefore, the primary objectives of this study are to: (1) quantify the impact of different spatial configurations of tributary sluice gate closures on the longitudinal extent of SI in the Tien River; and (2) assess how these closures affect salinity and freshwater availability at key locations. By isolating the effects of sluice gate infrastructure, this research aims to provide a nuanced scientific understanding to inform more strategic and sustainable water management planning.

2. DATA AND METHODOLOGY

2.1 Study area

The Tien River, a principal distributary of the Mekong River upon its entry into the VMD, is a critical source of freshwater for the expansive Plain of Reeds and several riverine provinces, including An Giang, Can Tho, and Vinh Long (Figure 1). Stretching approximately 234 km from the Cambodia–Vietnam border to its estuarine outlets at the East Sea, the Tien River bifurcates lower of the My Thuan Bridge into multiple smaller distributaries (Vu et al. 2024). These include the Co Chien, Ham Luong, Ba Lai, Cua Dai, and Cua Tieu Rivers, which form a complex network delivering freshwater to the coastal zone and interacting with tidal influences (Nguyen et al. 2023).

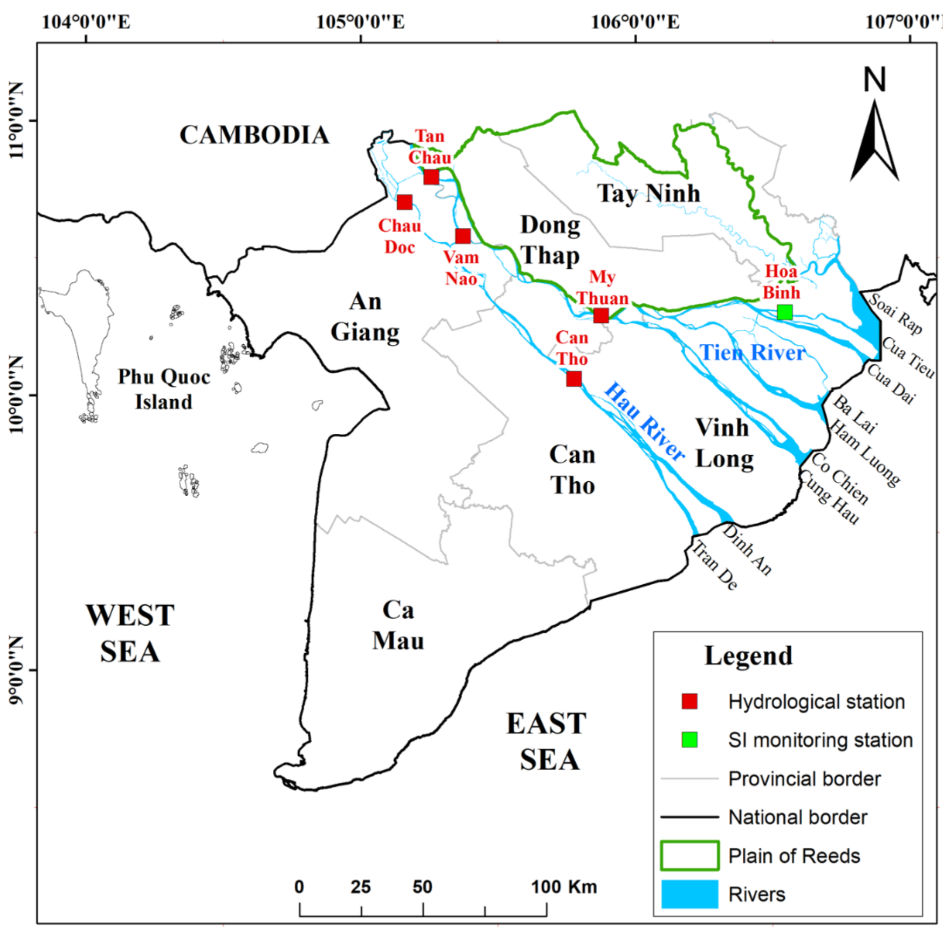

Figure 1 Study area and location of hydrological and salinity monitoring stations.

Hydrologically, the Tien River exhibits pronounced seasonal variations. During the dry season, typically from December to April, discharges at the Tan Chau gauging station (near the Cambodian border) range between 1,200 m^3/s and 1,800 m^3/s (Van Binh et al. 2020;

Duc Tran et al. 2024). Under these low-flow conditions, tidal forces from the East Sea can propagate more than 60 km inland (Eslami et al. 2019; Hoang et al. 2019). This interaction between reduced river discharge and strong tidal influence governs the dynamics and extent of SI in the estuarine and riverine system (Eslami et al. 2019; Loc et al. 2021). The study area is characterized by a tropical monsoon climate, with average annual temperatures between 26.7°C and 27.9°C, mean wind speeds from 2.0 to 2.5 m/s, and annual precipitation ranging from 1,300 to 2,040 mm (Lee and Dang 2018; Dinh and Dang 2022). Rainfall is unevenly distributed, with nearly 90% occurring during the wet season (May to November), which significantly increases the risk of SI during the subsequent dry season (Lee and Dang 2018).

2.2 Data

This investigation utilized hydrological and salinity data collected during the dry seasons of March 2016 and February 2020, selected to encompass periods of significant SI and to provide robust datasets for model calibration and validation. As summarized in Table 1, the observational data included: Hourly water level (H) and flow discharge (Q) from five principal hydrological stations: Tan Chau, Chau Doc, Vam Nao, My Thuan, and Can Tho (Figure 1). These stations are strategically distributed along the Tien and Hau Rivers, providing comprehensive information on upper and lower hydraulic dynamics.

Table 1 Summary of hydrological and salinity data.

Station	Parameter	Data availability	Location
Calibration and validation data:			
Tan Chau	*H, Q*	2016, 2020 (hourly data)	Tien River
Chau Doc	*H, Q*		Hau River
Vam Nao	*H, Q*		Vam Nao River
My Thuan	*H, Q*		Tien River
Can Tho	*H, Q*		Hau River
Hoa Binh	*S*		Tien River
Boundary condition data:			
Kratie	*Q*	2016, 2020 (hourly data)	Mekong River (Cambodia)
Vam Kenh, An Thuan, Ben Trai, Ganh Hao, My Thanh, Rach Gia, Song Doc	*H, S*		River-mouth and coastal stations (Figure 3)

NOTE: water level (H), flow discharge (Q), salinity concentration (S).

For salinity data (S), hourly time-series of salinity concentrations from the Hoa Binh station were used for calibration and validation within the main river, while hourly salinity data from nine coastal and river mouth stations (e.g., Vam Kenh, An Thuan) were used to prescribe the dynamic seaward boundary conditions.

Most observational data were obtained from the previous project KHCN-TNB.ĐT/14-19/C11 and other relevant Vietnamese government agencies. Extra observational data were supplemented by field surveys where necessary to ensure high resolution and reliability for model development. These data undergo rigorous quality control and assurance procedures by the issuing agencies prior to dissemination; therefore, they were considered reliable for model input, and no further handling of missing values was required. This use of high-resolution, quality-controlled hourly data is crucial for accurately simulating the dynamic nature of SI under varying hydrological conditions.

In addition to these hydro-meteorological time-series, comprehensive information regarding the river and canal network geometry, including cross-sectional profiles, locations and specifications of existing sluice structures, and their operational procedures, was collected. This information was primarily sourced from the Southern Institute for Water Resources Research in Vietnam (SIWRR) and was essential for accurately developing the MIKE 11 model for the Mekong Delta region.

2.3 Methodology

Research framework

The methodological approach of this study followed a structured workflow, illustrated in Figure 2, which comprised five main steps:

1. Data collection and processing: Hydrological data (water level, flow discharge, salinity), river and canal network configurations, cross-sectional profiles, sluice gate details, and other relevant information (as detailed in Table 1) were collected and processed to create a comprehensive input dataset for the hydraulic and salinity modeling of the VMD region.
2. MIKE 11 model setup: A one-dimensional (1D) hydrodynamic and salinity transport model was developed by Danish Hydraulic Institute (DHI). The computational domain extended from Kratie (Cambodia) and the Tonle Sap Lake outlet to the various estuarine mouths discharging into the East Sea of Vietnam.
3. Model calibration and validation: The model was calibrated using observed data from March 2016, a period characterized by severe SI. Validation was subsequently performed using data from February 2020, also a significant SI period. Model performance was quantitatively assessed using standard statistical metrics: the Pearson correlation coefficient (r) and the Nash–Sutcliffe Efficiency (NSE).

4. Model performance evaluation: The calibration and validation results were evaluated against established performance thresholds for hydrological models (e.g., Moriasi et al. 2007). A model meeting acceptable criteria (typically $r > 0.7$ and NSE > 0.5 for key parameters) was considered well-calibrated and suitable for subsequent scenario simulations.
5. Scenario-based evaluation: Using the calibrated model, a series of hypothetical sluice gate configurations (Scenarios S1–S5) along the Tien River tributaries were simulated. These scenarios were designed to assess the impacts of sluice placements on salinity intrusion patterns (SIPs), specifically focusing on the Tieu estuary. The results from these scenarios were compared to a baseline scenario (S0), which represented the actual conditions observed in 2016.

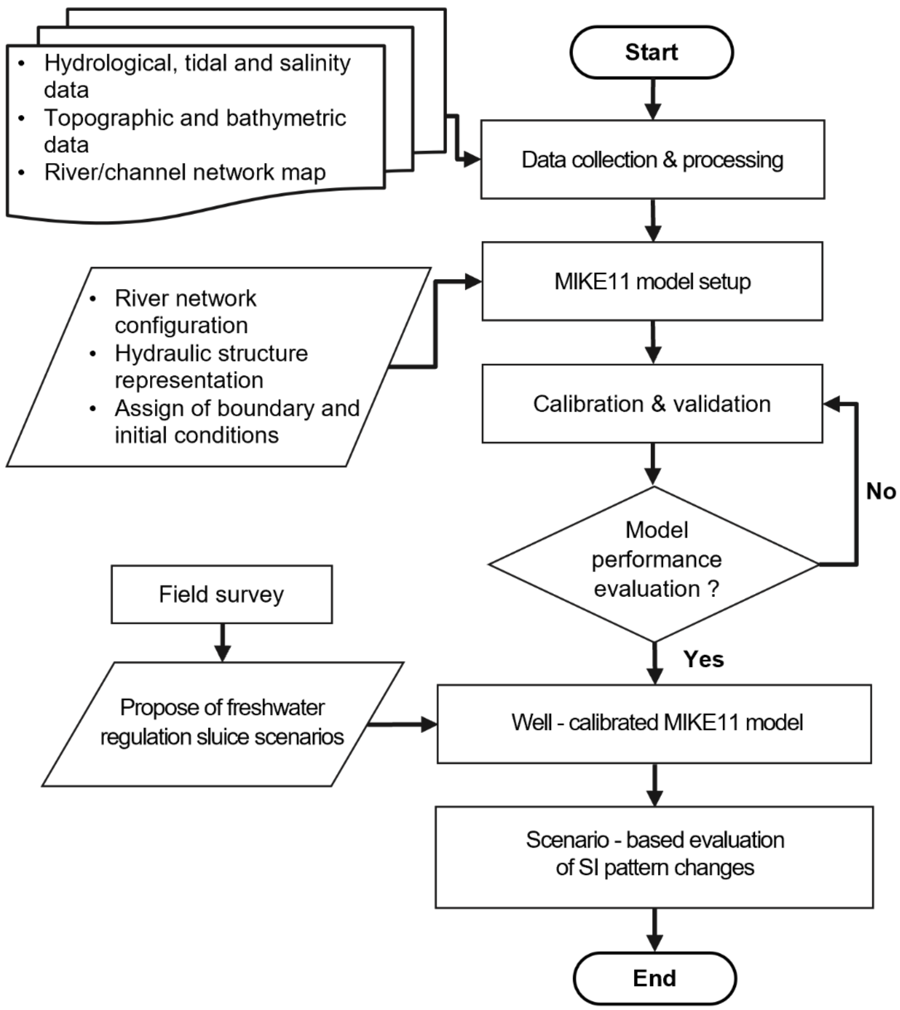

Figure 2 Methodology framework.

MIKE 11 model setup

MIKE 11 software, a 1D hydrodynamic modeling system developed by the Danish Hydraulic Institute (DHI), served as the core tool for simulating flow dynamics and SI within the intricate river network of the VMD (Anh et al. 2018; Tran et al. 2020). The model was configured using several key components: a detailed river network, representative cross-sections, existing and hypothetical sluice structures, appropriate boundary conditions (both upper and downstream), and calibrated hydraulic and salinity advection-dispersion parameters (DHI 2014; Duc Tran et al. 2024).

The hydrodynamic module (HD) of MIKE 11 was employed to simulate the hydraulic regime (DHI 2014). This module solves the Saint-Venant equations, which consist of the continuity equation and the momentum equation, describing 1D unsteady open channel flow. The advection-dispersion (AD) module was subsequently applied to simulate the transport and mixing of salinity (DHI 2014). Detailed theoretical descriptions of the Saint-Venant equations and the advection-dispersion formulation used in MIKE 11 can be found in the DHI (2014) software documentation.

The computational network of the MIKE 11 model applied for this work is illustrated in Figure 2. It encompassed 12 upper boundaries (including Kratie, the Tonle Sap, and Vam Co Dong), 70 downstream boundaries, 995 river/canal branches, approximately 15,000 computational nodes (grid points), 9,400 cross-sections, and 160 major existing sluice structures (Figure 3). Initial conditions for the simulations were set with a water level of approximately 0.5 m (above a reference datum) for all river branches, an initial discharge of 0 m^3/s throughout the network, and an initial salinity concentration of 0‰ (equivalent to g/L) at all boundaries, except for the sea boundaries.

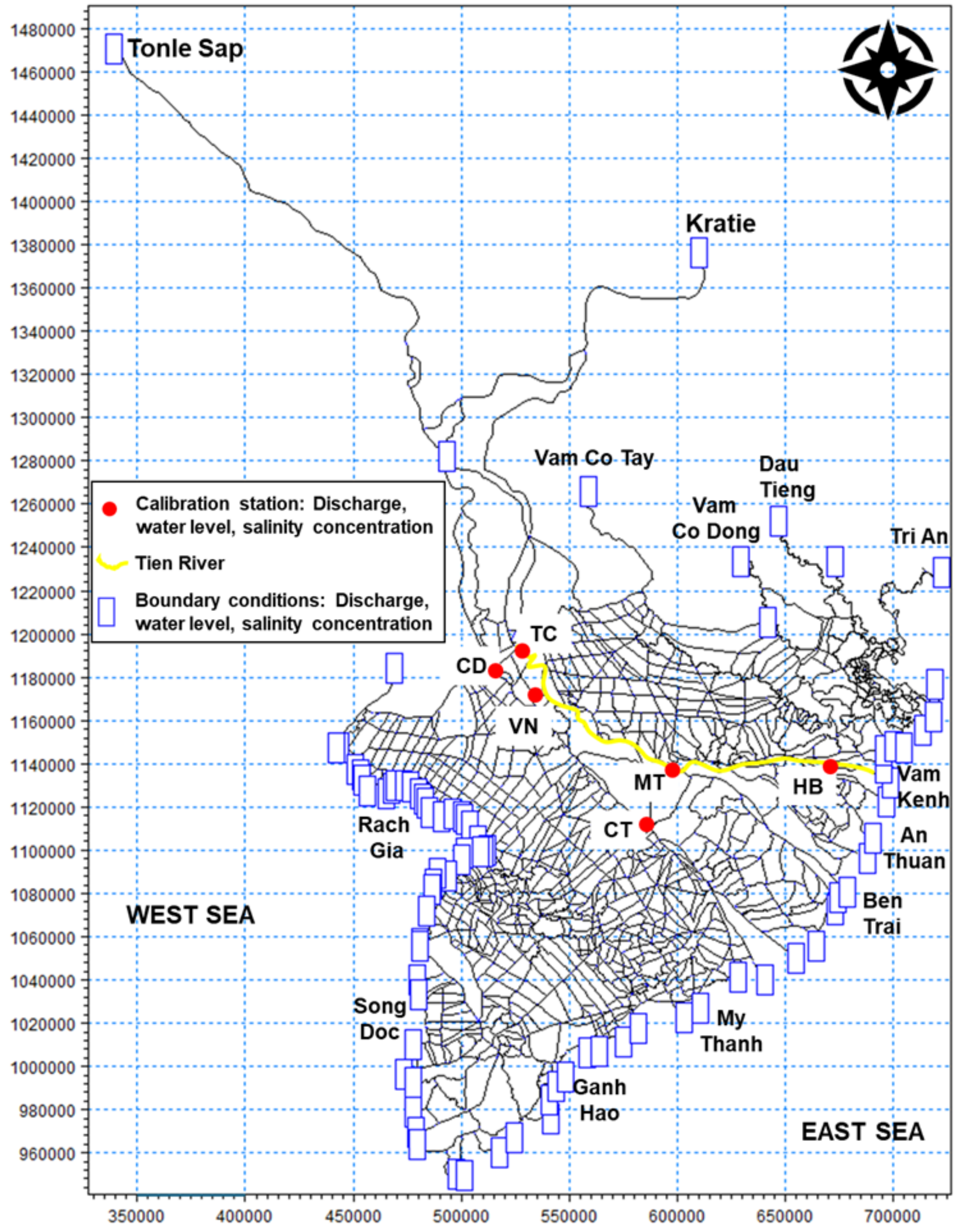

Figure 3 Scheme of river network modeling, with clear labels for CD, TC, VN, MT, CT, and HB as defined in the note.

The key parameter for the calibration and validation of the HD module was the Manning's roughness coefficient (*n*). This coefficient was varied spatially, ranging from 0.010 to 0.033, depending on the specific characteristics of different sub-regions within the VMD. For the AD module, the primary calibration parameter was the longitudinal dispersion coefficient, which was set to values between 100 and 1,200 m^2/s based on channel characteristics and flow conditions.

Development of proposed scenarios

To investigate the potential influence of new or altered sluice gate operations on SIPs in the Tien River, a series of six scenarios (S0–S5) was set up and simulated. These scenarios were specifically designed to assess the spatial effects of sluice placements across different regions of the Tien River's tributary network—namely, the upper, middle, and lower reaches relative to the estuarine zone. The primary goal was to evaluate how variations in the distribution and operation (assumed closed during critical periods) of sluice gates affect key salinity parameters, including intrusion length (defined by the 4 g/L isohaline), salinity concentration profiles, and freshwater exposure duration.

Baseline scenario (S0): This scenario was configured using the actual sluice structure data and operational status from the year 2016. The year 2016 was selected as it represents a significant SI event for which comprehensive and high-quality observational data are available. This provides a robust and verifiable baseline against which to measure the impact of interventions, as opposed to a more extreme drought year like 2020 where multiple confounding factors (e.g., anomalous upstream flow) were at play.

For all intervention scenarios (S1-S5), sluice gates were assumed to be fully closed during the simulation period. This represents a worst-case operational assumption designed to evaluate the maximum potential hydrodynamic impact of these structures. While real-world operations may be more dynamic (e.g., partial opening), this approach allows for a clear, conservative assessment of their influence. However, implementing dynamic gate operation in practice is challenging within the current context of the study area. This is due to operational difficulties and the challenges in accurately forecasting salinity levels, which are necessary for making timely decisions on opening or closing the sluice gates. In reality, the gates are typically kept fully closed and are only opened upon a directive from the competent local authorities, specifically the Provincial People's Committees governing the areas where these salinity control structures are located.

Scenario S1 (maximum intervention): This scenario assumed the installation and closure of sluices across all 16 identified major branch channels (T1–T16, as shown in Figure 4) feeding into the Tien River. This represents the maximum plausible extent of freshwater retention and saltwater intrusion prevention infrastructure development.

Scenario S2 (upper tributaries): This scenario evaluated the impact of sluices located only in the upper tributaries (T1–T6).

Scenario S3 (midstream tributaries): This scenario focused on the effect of sluices in the midstream tributaries (T7–T11).

Scenario S4 (lower tributaries): This scenario assessed the influence of sluices positioned in the lower tributaries (T12–T16), closer to the estuarine zone.

Scenario S5 (localized lower tributaries): This scenario examined a more focused sluice arrangement in a specific subsection of the lower tributaries (T12–T13) to test a more localized impact approach.

The spatial layout of these assumed sluice gate positions is illustrated in Figure 4. Table 2 provides a concise summary of the tributary groups included in each scenario. This systematic approach allows for a comprehensive comparison of upper, midstream, and downstream sluice effects on SI dynamics in the main Tien River under dry-season conditions.

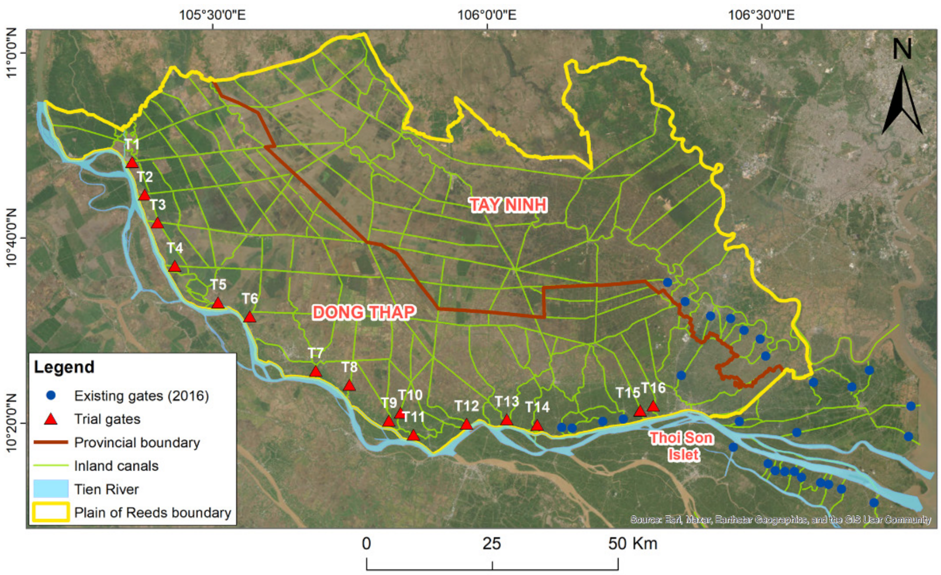

Figure 4 Location of assumed sluice gates.

Table 2 Summary of the scenarios.

Scenarios	Closed sluice gates	Note
S1	T1 to T16	For all assumed sluice gates
S2	T1 to T6	For all sluice gates in the upper part
S3	T7 to T11	For all sluice gates in the middle part
S4	T12 to T16	For all sluice gates in the lower part
S5	T12 to T13	For a part of sluice gates in the lower part

3. RESULTS

3.1 MIKE 11 model calibration and validation performance

The MIKE 11 model, configured for the VMD's intricate river network, underwent a rigorous two-stage calibration and validation process to ensure its reliability for simulating hydrodynamics and salinity transport in subsequent scenario analyses. Calibration was performed using observed data from March 2016, a period characterized by significant SI, while validation utilized data from February 2020, another period with notable SI events. These periods provided robust conditions for testing model performance. Quantitative evaluation involved comparing simulated and observed water levels and flow discharges at five principal hydrological stations (Tan Chau, Chau Doc, Vam Nao, My Thuan, and Can Tho) and salinity at Hoa Binh station. The primary statistical indices for performance assessment were the *r* and the NSE.

The applied model demonstrated excellent performance across all five stations (Table 3). During the calibration phase (March 2016), *r*-values for water levels ranged from 0.98 to 0.99, with corresponding NSE values between 0.86 (Chau Doc) and 0.96 (My Thuan and Can Tho). For discharge, *r*-values ranged from 0.93 (Chau Doc) to 0.98 (Tan Chau, My Thuan), and NSE values ranged from 0.86 (Chau Doc) to 0.93 (My Thuan). The model also maintained strong performance during the validation phase (February 2020). Water level *r*-values remained high, ranging from 0.92 (Vam Nao) to 0.96 (Tan Chau), with NSE values from 0.78 (Vam Nao) to 0.91 (Tan Chau). The *r*-values of flow discharge spanned from 0.94 (Chau Doc) to 0.98 (My Thuan), with NSE values from 0.85 (Chau Doc) to 0.93 (My Thuan). These high correlation coefficients and NSE values generally exceed the recommended thresholds of $r > 0.7$ and $NSE > 0.5$ for good model performance (Moriasi et al. 2007), which confirms the hydrodynamic module's reliability in reproducing observed conditions. Graphical comparisons of observed and simulated water levels and discharges at My Thuan station for calibration and validation periods (Figures 5 and 6) visually affirm the model's capability to accurately capture both the magnitude and temporal variations of hydrodynamic conditions.

Table 3 Summary of performance statistics during the hydrodynamic calibration and validation periods.

Year	Parameters	Tan Chau		Chau Doc		Vam Nao		Can Tho		My Thuan	
		r	NSE	*r*	NSE	*r*	NSE	*r*	NSE	*r*	NSE
2016	*H*	0.98	0.93	0.98	0.86	0.98	0.91	0.98	0.96	0.99	0.96
(Calibration)	*Q*	0.98	0.92	0.93	0.86	0.95	0.87	0.97	0.93	0.96	0.92
2020	*H*	0.96	0.91	0.91	0.76	0.92	0.78	0.92	0.83	0.94	0.86
(Validation)	*Q*	0.94	0.88	0.94	0.85	0.96	0.80	0.96	0.91	0.98	0.93

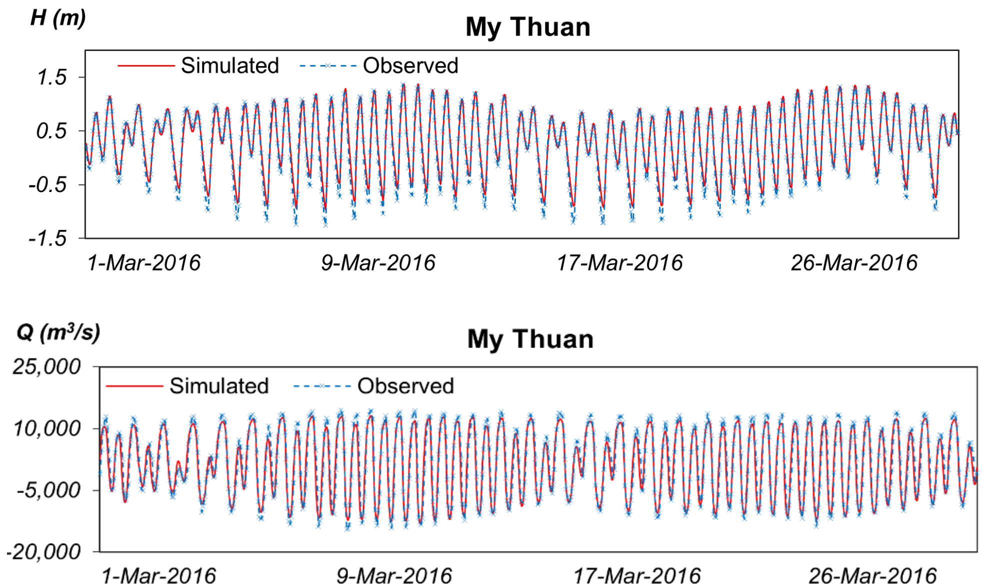

Figure 5 Comparison of observed and simulated water level and discharge at My Thuan station during the calibration period (March 1–31, 2016).

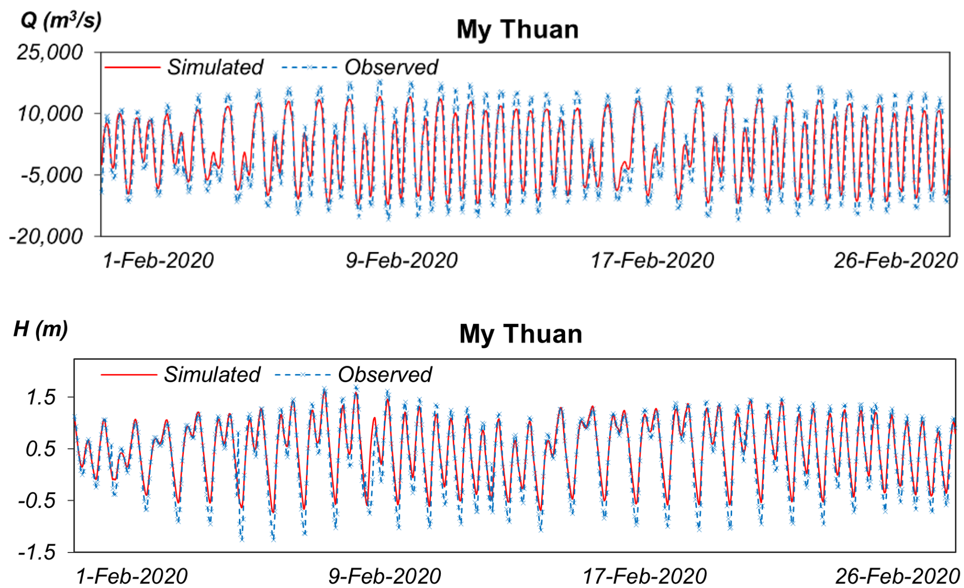

Figure 6 Comparison of observed and simulated discharge and water level at My Thuan station during the validation period (February 1–28, 2020).

Following hydrodynamic calibration, salinity calibration and validation were performed using data from Hoa Binh station (Table 4). During calibration (March 2016), the model yielded an *r*-value of 0.87 and an NSE of 0.55 for salinity. In the validation period (February 2020), the *r*-value was 0.72 and the NSE was 0.50. While these correlation coefficients for salinity were slightly lower than those for hydrodynamic parameters, the performance metrics, particularly the NSE values, met or exceeded the acceptable threshold of NSE > 0.50 for this key observation point. This indicates a satisfactory representation of large-scale estuarine salinity dynamics by the model, consistent with recommendations for similar modeling applications (Tran et al. 2020). Visual comparisons of observed and simulated salinity concentrations at Hoa Binh station during calibration and validation (Figures 7 and 8) further illustrate reasonable agreement.

Table 4 Summary of performance statistics during the salinity calibration and validation periods.

Year	Phase	Hoa Binh	
		r	NSE
2016	Calibration	0.87	0.55
2020	Validation	0.72	0.50

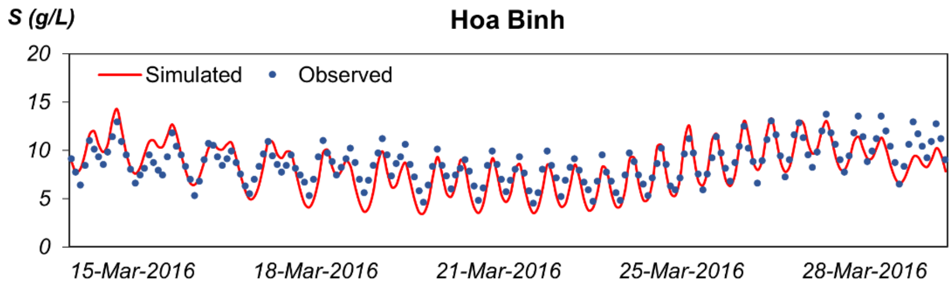

Figure 7 Comparison of observed and simulated salinity at Hoa Binh station during the calibration period (March 16–31, 2016).

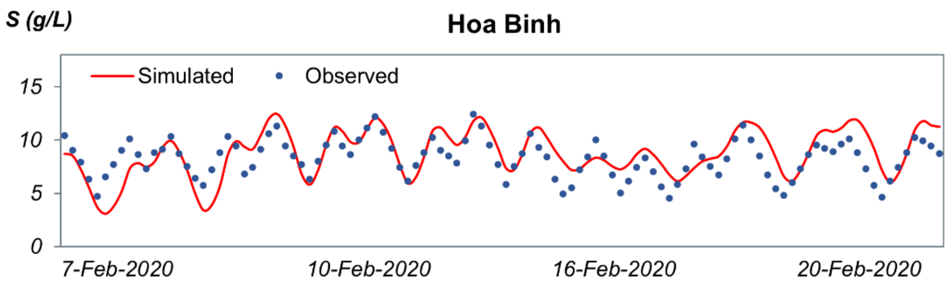

Figure 8 Comparison of observed and simulated salinity at Hoa Binh station during the validation period (February 7–22, 2020).

In summary, the comprehensive calibration and validation results for both hydrodynamics and salinity affirm that the applied MIKE 11 model is reliably accurate and suitable for simulating SI phenomena across the study area. It is therefore considered appropriate for the subsequent evaluation of sluice gate scenario impacts.

3.2 Assessing the impact of sluice gates on salinity intrusion patterns

The MIKE 11 model was subsequently employed to evaluate the influence of hypothetical freshwater regulation sluice gates on SIPs along the Tien River. This assessment was conducted through a series of scenario-based simulations (S1–S5), which were systematically compared against a baseline scenario (S0) representing actual 2016 conditions. The evaluation focused on three primary indicators: the maximum inland extent of the 4 g/L salinity concentration isohaline, temporal changes in salinity concentration at specific locations, and the duration for which freshwater (defined as salinity < 4 g/L) was accessible at selected sites.

Spatial extent of salinity intrusion

Figure 9 illustrates the maximum inland penetration of the 4 g/L salinity front for each simulated scenario, providing a clear depiction of how different sluice gate configurations influence the spatial reach of SI. Under baseline conditions, representing the actual state in 2016, the 4 g/L saline front extended approximately 52.5 km inland from the Cua Tieu mouth, reaching near the T16 sluice gate location and the Thoi Son islet.

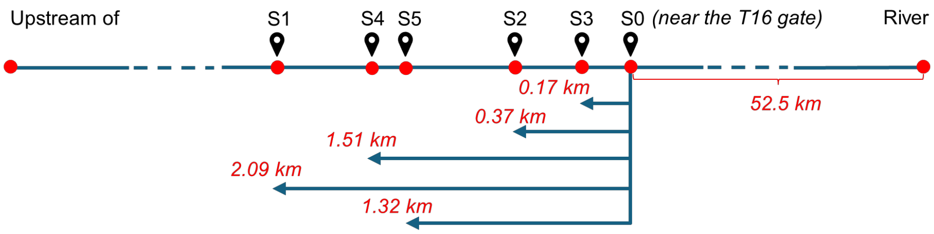

Figure 9 Demonstration of the 4 g/L salinity concentration extent on the Tien River across scenarios, compared to the baseline scenario (S0).

Scenario S1, which simulated the closure of sluices across all 16 identified major tributaries (T1–T16), resulted in the most significant increase in SI. In this scenario, the 4 g/L isohaline advanced an additional 2.09 km upper compared to the baseline.

Scenarios involving sluice gates located in the lower part of the river also demonstrated substantial impacts. Scenario S4 led to a salinity front advancement of 1.51 km. Scenario S5, a more localized intervention involving the closure of sluices T12–T13 in the lower tributaries, still caused a notable advancement of 1.32 km.

In contrast, scenarios representing sluice closures in the upstream (S2: T1–T6 closed) and midstream (S3: T7–T11 closed) regions exhibited only marginal impacts on the maximum intrusion length. The 4 g/L saline front advanced by a mere 0.17 km in S2 and 0.37 km in S3.

These results clearly indicate that the strategic location of sluice gates is a critical determinant of their impact on main river SI. Closures in the lower, more estuary-proximal tributaries demonstrate a far greater potential to exacerbate salinity penetration than those sluices situated further upstream.

Temporal salinity variations and freshwater availability

Figures 10 and 11 present the temporal variations in salinity concentration at a representative location (30 km from the river mouth) for scenarios S1 and S5, respectively, compared to the baseline S0. These plots illustrate that the installation and operation (closure) of sluice gates not only increase peak salinity concentrations but also extend the duration for which salinity remains above the critical 4 g/L threshold, thereby reducing freshwater availability.

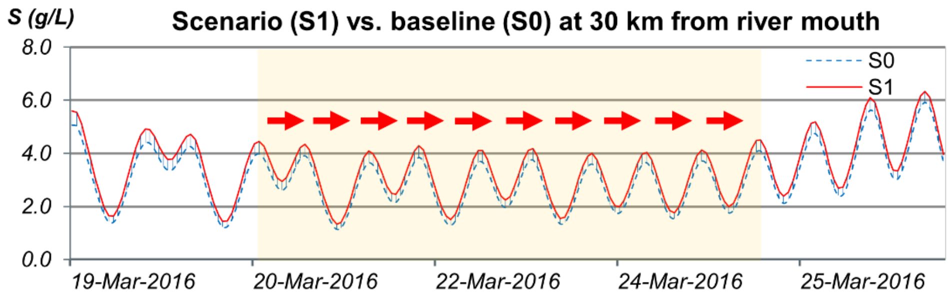

Figure 10 Comparison of salinity over time between scenarios S1 and S0.

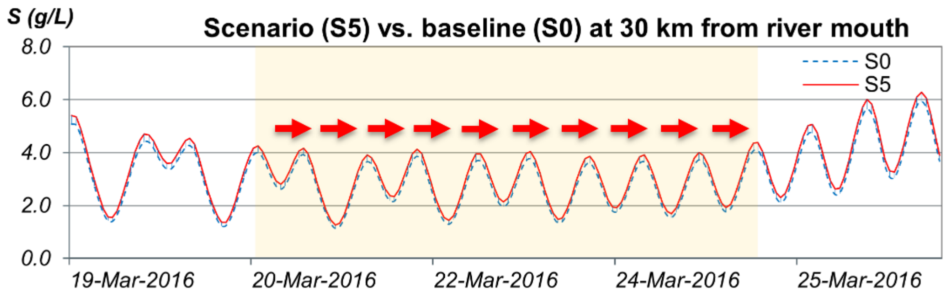

Figure 11 Comparison of salinity over time between scenarios S5 and S0.

Table 5 quantifies these changes, detailing the percentage increase in average salinity concentration (during periods when S > 4 g/L) and the corresponding reduction in freshwater intake hours (time when S < 4 g/L) at distances of 20, 30, and 40 km from the river mouth for each scenario.

Table 5 Summary of salinity and freshwater intake hour reductions at typical Tien River locations under various scenarios.

Distance from river mouth (km)	Scenarios				
	S1	S2	S3	S4	S5
	ΔS (%) / ΔT (h)	ΔS (%) / ΔT (h)	ΔS (%) / ΔT (h)	ΔS (%) / ΔT (h)	ΔS (%) / ΔT (h)
40	12.6/22	0.87/1	0.91/2	10.65/22	8.6/19
30	10.0/34	0.62/1	0.70/1	8.63/26	6.9/20
20	7.9/21	0.44/3	0.55/3	6.92/18	5.6/15

Scenario S1 produced the most severe impacts. Salinity concentrations increased by 12.6% at 40 km, 10.0% at 30 km, and 7.9% at 20 km from the mouth. Correspondingly, freshwater availability declined significantly, with reductions of 22 hours at 40 km, 34 hours at 30 km, and 21 hours at 20 km over the simulated critical period.

Scenario S4 also yielded substantial effects. Salinity increased by 10.65% (at 40 km), 8.63% (at 30 km), and 6.92% (at 20 km). Freshwater availability reductions were 22 hours (40 km), 26 hours (30 km), and 18 hours (20 km), respectively.

Scenario S5, despite involving fewer closed gates, still exhibited a strong influence. Salinity increased by 8.6% at 40 km, with a corresponding reduction in freshwater intake by 19 hours at that location. Impacts varied at other locations as detailed in Table 5 (e.g., 6.9% increase / 20-hour reduction at 30km; 5.6% increase/15-hour reduction at 20km).

Scenarios S2 and S3 induced only marginal changes. Salinity increases were generally less than 1.0%, and reductions in freshwater intake time were limited to 1–3 hours. This indicates a minimal impact on mainstem salinity dynamics from sluices positioned in these more upper locations.

Relationship between sluice location, discharge, and salinity impact

The results consistently demonstrate that sluice gates positioned closer to the river mouth exert a more pronounced influence on SI dynamics in the Tien River compared to those situated further upstream. Figure 12 provides further insight by illustrating the average discharge from each tributary branch canal into the main river alongside the corresponding distance (L, km) from each conceptual sluice gate (T1–T16) to the 4 g/L salinity boundary observed in the 2016 baseline (S0).

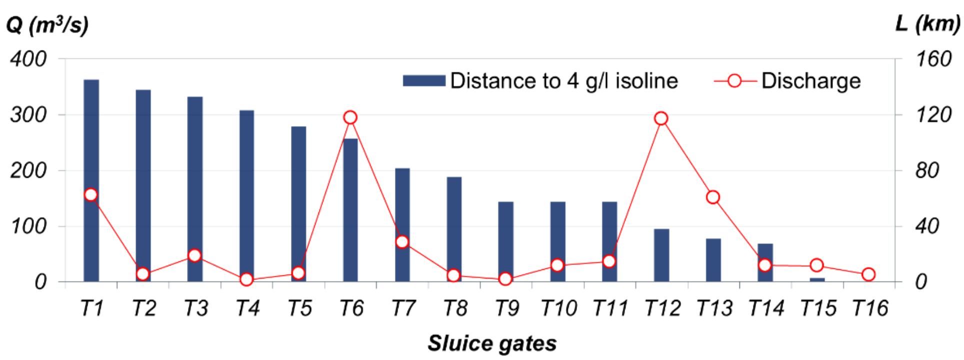

Figure 12 Illustration of the distance between the sluices, and the 4 g/L salinity extent in 2016, along with the corresponding discharge at each sluice.

The analysis reveals that sluices positioned along tributary canals characterized by both high discharge contributions and close proximity to the existing salinity boundary (i.e., low L values) tend to most significantly intensify SI. For example, in Scenario S5, the closure of sluices T12 and T13—located 38 km and 30 km, respectively, from the S0 salinity boundary and with average discharges of 292.92 m^3/s and 151.15 m^3/s—caused the 4 g/L isohaline to advance 1.32 km. This configuration directly impedes freshwater flushing capacity at critical points near the saline front, thereby facilitating further upstream saltwater propagation.

Conversely, sluices such as T1 and T6, although associated with relatively high discharge rates (156 m^3/s and 294 m^3/s, respectively), are located much farther from the 4 g/L boundary (145 km and 103 km, respectively). Consequently, their closure exhibits minimal influence on SI in the main river, as their freshwater contribution occurs well upper of the typical saline extent during the dry season. This contrast highlights the spatial sensitivity of sluice impacts: proximity to the dynamic estuarine zone plays a more dominant role in modifying main river salinity dynamics than the absolute discharge volume of the tributary alone, although both factors are relevant. Sluices on high-discharge tributaries situated near the estuary have a dual adverse effect: they reduce a significant freshwater inflow that would otherwise help repel saline water, and they can contribute to creating a more stagnant zone, allowing tidal forces to push saline water further inland.

4. DISCUSSION

The results of this work unequivocally demonstrate that the strategic placement and operation of sluice gates within the tributaries of the Tien River exert a measurable, and in certain scenarios significant, impact on SIPs within the main river. A key outcome is the disproportionate influence of lower sluice placements, particularly those on high-discharge tributaries near the estuarine zone. By diminishing freshwater flushing capacity at critical locations, these sluices effectively amplify the inland penetration of SI. This phenomenon arises because these lower tributaries contribute a substantial volume of freshwater that directly counteracts SI; their closure not only removes this vital buffer but can also alter local tidal hydrodynamics, potentially enhancing landward salt transport mechanisms, as suggested by Eslami et al. (2021).

These results underscore the complex interplay among tributary freshwater discharge, tidal dynamics, and main river salinity. While sluices are primarily intended to protect localized agricultural cultivation areas from salinization and retain freshwater resources, their collective impact, if not meticulously evaluated, can precipitate unintended adverse consequences for the broader river system. The observation that closing all 16 identified tributary sluices (Scenario S1) induced an approximately 2 km advancement of the 4 g/L isohaline and a significant reduction in freshwater availability (up to 34 hours at 30 km from the mouth) highlights the potential for widespread sluice implementation to exacerbate regional water stress. Notably, even more localized interventions in the lower reaches (Scenario S5) yielded substantial impacts, comparable in magnitude at specific locations to scenarios involving more extensive sluice closures further upstream, further emphasizing the sensitivity of the lower river system.

This study's findings align with concerns raised by Van Binh et al. (2020) and expand upon them by isolating the specific role of sluice infrastructure. The VMD is already a system under stress from multiple drivers, including reduced upstream flows, land subsidence, and global SLR (Eslami et al. 2021; Minderhoud et al. 2017). Our results show that poorly planned local infrastructure can act as a potent stress multiplier.

This phenomenon is not unique to the Mekong Delta. Other major deltas face similar challenges where local water management interventions interact with large-scale environmental changes. In the Ganges-Brahmaputra-Meghna Delta, for instance, coastal polders and sluices designed to protect against cyclones and salinity have altered sedimentation patterns and tidal dynamics, sometimes exacerbating waterlogging and local salinity issues (Bricheno et al. 2021; Sherin et al. 2020). Similarly, in the Nile Delta, the reduction of freshwater flow due to the Aswan High Dam, combined with SLR, has led to severe coastal erosion and groundwater salinization, a situation where local irrigation controls struggle to mitigate (An et al. 2021). What this study adds to this global context is a quantitative demonstration of how a distributed network of smaller-scale structures (tributary sluices) can collectively induce a large-scale, system-wide impact on the main distributary channel, a crucial insight for regions planning similar interventions.

The minimal impact observed from closing upper and midstream sluices (Scenarios S2 and S3) suggests that interventions far from the active saline front are less likely to adversely affect main river salinity. This provides a crucial insight into future infrastructure planning: prioritizing sluice locations based on a thorough understanding of their potential hydrodynamic feedback is essential. A blanket approach to sluice construction across all tributaries, without considering their specific location and discharge characteristics relative to the salinity front, could be counterproductive.

The implications for freshwater management in the VMD are considerable. The construction of salinity control sluices is a prioritized structural measure in response to escalating SI risks (Minderhoud et al. 2017; MRC 2020). However, this research suggests that such interventions, particularly in the lower reaches of major distributaries like the Tien River, require comprehensive environmental and hydrodynamic impact assessments before implementation.

Based on these findings, we propose more concrete management guidance:

- A zonal management approach: Moving forward, a paradigm shift from widespread hydraulic control to a zonal management framework is advisable. The objective of such a framework would not be the complete desalinization of estuarine reaches, but rather the preservation of their inherent hydro-ecological characteristics. To illustrate, the lower 40–50 km of the Tien River estuarine system could be designated a 'Zone of Restricted Hydraulic Intervention.' Within this demarcation, the installation of new sluices on tributaries with significant discharge would be limited to safeguarding the integrity of the natural brackish-to-freshwater continuum.

- Cumulative impact assessments: Any new infrastructure proposal must be evaluated not in isolation, but within a cumulative impact assessment framework that models its interaction with existing structures and projected changes in SLR and upstream flows.
- Adaptive operational rules: Instead of static "open/closed" policies, developing dynamic, real-time operational rules for sluice gates, informed by real-time monitoring and hydrodynamic forecasting models, is essential to balance local protection with system-wide health.

Limitations and future research

It is important to acknowledge the limitations of this study. First, the use of a 1D MIKE 11 model, while efficient for large river networks, simplifies complex hydrodynamic and mixing processes that occur in three dimensions, particularly in wider estuarine sections. The results should therefore be interpreted as representing large-scale, channel-averaged dynamics.

Second, this study did not include a formal sensitivity or uncertainty analysis on key model parameters like Manning's roughness coefficient or the longitudinal dispersion coefficient. While these parameters were carefully selected based on a thorough calibration process and values reported in previous studies for the region, a formal analysis would further strengthen confidence in the precise quantitative outcomes.

Third, the scenarios assumed complete and continuous closure of sluices during the critical dry season. As previously noted, this represents a simplified, worst-case assumption. Real-world operations are often more dynamic and may involve partial openings. This simplification may lead to an overestimation of the impacts, but it serves the study's objective of identifying the locations of greatest potential influence.

Future research should build upon these findings. Employing 2D or 3D models for specific, critical estuarine reaches could provide deeper insights into mixing processes. Furthermore, future work should investigate optimized, real-time sluice operation rules and explore alternative scenarios beyond complete closure to better reflect potential management practices.

5. CONCLUSIONS

This study employed the MIKE 11 hydrodynamic-salinity model to comprehensively evaluate how varying spatial configurations of tributary sluice gate closures affect SI in the Tien River, a major distributary of the Mekong Delta. The research conclusively demonstrates that the location of sluice gates, rather than merely the total number of closures, plays a more critical role in determining the resultant impact on main river salinity.

Simulation results consistently revealed that closing sluice gates situated near the estuarine zone, particularly those on tributaries contributing significant freshwater discharge, led to a discernible landward shift of the 4 g/L salinity boundary and a concomitant reduction in freshwater availability upper within the Tien River. Notably, even the closure of a few strategically important lower gates (as in Scenario S5) substantially influenced SI. Conversely, operating sluice gates located further upstream or in midstream tributaries (Scenarios S2 and S3), or on tributaries with low-flow discharge, resulted in only negligible alterations to main river salinity dynamics.

These findings strongly suggest that insufficiently assessed sluice gate construction can inadvertently exacerbate SI in the Tien River. To avert such unintended negative consequences, future sluice planning and water infrastructure development in the Mekong Delta must meticulously consider local hydrodynamics, tidal influences, and the specific discharge characteristics of each tributary relative to the existing and projected saline front. This necessitates a shift from localized benefit analysis to a more holistic, system-wide impact assessment.

An integrated and adaptive approach to water resource management is therefore essential for the protection of freshwater resources and the enhancement of ecosystem resilience in the vulnerable Mekong Delta. This includes conducting thorough impact assessments prior to any new infrastructure development, and instituting ongoing monitoring and adaptive evaluation of existing structures and their operational regimes. The management of sluice systems, predicted by robust hydrodynamic modeling and field data, is paramount to achieving a sustainable balance between local freshwater protection and the overall health of the entire river system. Future research should build upon these findings by exploring the use of 2D/3D models for specific estuarine reaches and developing optimized, real-time sluice operation rules to maximize benefits while minimizing adverse system-wide impacts.

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