

Integrated Hydrodynamic-Ecological Assessment of Estuarine Barrage Operation Impacts on a Tropical Lagoon Ecosystem: A Case Study of Thao Long Dam in the Huong River-Tam Giang System, Vietnam

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How to cite this paper: Tuan, N. V., & Cuong, T. K. (2026). Integrated Hydrodynamic-Ecological Assessment of Estuarine Barrage Operation Impacts on a Tropical Lagoon Ecosystem: A Case Study of Thao Long Dam in the Huong River-Tam Giang System, Vietnam. *Journal of Geoscience and Environment Protection*, 14, 238-262. <https://doi.org/10.4236/gep.2026.146012>

Received: May 28, 2026

Accepted: June 26, 2026

Published: June 29, 2026

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Abstract

This study uses a sustainable coastal ecosystem approach to assess the impact of coastal river dams on ecosystems and aquatic environments, focusing on a case study model at the Thao Long saltwater intrusion control dam (Huong River basin) and the Tam Giang-Cau Hai lagoon system in Central Vietnam. Analysis results indicate that the operation of opening and closing the dam can create extreme changes in salinity levels, causing “freshwater shock,” increasing flow pressure and velocity downstream, and leading to stagnation and degradation of water quality upstream. Analysis of the physiological mechanisms, osmotic pressure regulation, and migration patterns of indicator species with high ecological and economic value in the area, including brown fish, sea bass, perch, shrimp, and native clams, shows that aquatic communities are vulnerable when salinity ranges exceed tolerance thresholds (commonly 15‰ - 32‰). The construction of a dam across the river mouth, such as the Thao Long Dam, which is closed during the dry season, also has negative impacts by disrupting the natural connection between the river and the sea, causing significant disturbances to the migration patterns, reproduction, life cycles, and diversity of common fish species in the Huong River estuary. This study contributes a novel integrated eco-hydraulic framework combining hydrodynamic modeling, salinity shock analysis, and ecological connectivity assessment for evaluating the impacts of estuarine barrage operations in tropical lagoon systems.

Keywords

Estuarine Ecology, Salinity Range, Ecological Connectivity, Thao Long Dam

 Operation

1. Introduction

Estuarine and lagoon ecosystems are among the most productive and ecologically sensitive transitional environments in the world, providing essential ecosystem services including biodiversity conservation, fisheries production, nutrient cycling, water purification, and coastal protection (Costanza et al., 1997; Barbier et al., 2011). Tropical estuarine lagoons, in particular, function as critical ecological interfaces between riverine and marine systems, where hydrodynamic exchange processes regulate salinity gradients, sediment transport, nutrient dynamics, and habitat connectivity for numerous aquatic species (Kennish, 2002; Wolanski & Elliott, 2015). However, these systems are increasingly threatened by climate change, sea-level rise, freshwater scarcity, and intensive hydraulic infrastructure development (Nicholls & Cazenave, 2010; IPCC, 2021).

In many coastal regions worldwide, estuarine barrages and salinity-control structures have been widely constructed to mitigate saline intrusion, secure freshwater resources, support agricultural production, and reduce flood risks (McCartney & Sally, 2007; Bice et al., 2023). While these structures provide significant socio-economic benefits, their operations frequently alter natural hydrodynamic regimes, disrupt estuarine circulation, and modify salinity distributions within downstream lagoons and coastal wetlands (Williams et al., 2014; Gillanders et al., 2011). Previous studies have demonstrated that prolonged barrage closure can reduce tidal exchange, increase water stagnation, and intensify ecological degradation in estuarine environments, whereas sudden gate opening and flood releases may induce rapid salinity fluctuations that exceed the adaptive capacity of estuarine organisms (Khalil et al., 2025; Zhang et al., 2022).

Beyond hydrological alterations, estuarine barrage operations may generate substantial ecological consequences by disrupting ecological connectivity between freshwater, estuarine, and marine habitats (Able, 2005; Nagelkerken et al., 2000). Many estuarine fish and aquatic organisms depend on seasonal salinity gradients and hydrodynamic cues to complete migration, spawning, larval transport, and feeding processes (Whitfield et al., 2012; Bice et al., 2023). Changes in flow regimes and salinity transition rates may therefore affect physiological osmoregulation, habitat suitability, biodiversity patterns, and ecosystem resilience (Elliott & Whitfield, 2011). In tropical lagoon systems, where biological productivity and species interactions are strongly controlled by salinity dynamics, abrupt freshwater or hypersaline conditions can trigger severe ecological stress and habitat degradation (Ethan & Catherine, 2022; Zhang et al., 2022).

Despite growing concerns regarding the environmental impacts of estuarine barrages, most previous studies have primarily focused on hydrological regulation, salinity intrusion control, or water resource management. Integrated assess-

ments simultaneously addressing hydrodynamic alterations, ecological connectivity disruption, and species-specific physiological responses remain limited, particularly in tropical estuarine lagoons of Southeast Asia. In addition, the combined impacts of upstream reservoir operations and downstream barrage regulation on estuarine ecosystems have rarely been evaluated within a unified ecohydraulic framework (McCartney & Sally, 2007; Wolanski & Elliott, 2015). Existing studies commonly assess salinity conditions based on seasonal averages or static spatial distributions, while the temporal rate of salinity variation—a key driver of osmotic stress and ecological disturbance—has not been sufficiently quantified (Zhang et al., 2022; Zhao et al., 2013).

The Tam Giang-Cau Hai lagoon system in Central Vietnam represents one of the largest tropical brackish lagoon systems in Southeast Asia and supports highly diverse ecological and socio-economic functions. The lagoon receives freshwater inflows primarily from the Huong River basin and exchanges water with the East Sea through the Thuan An inlet. To control salinity intrusion and secure freshwater for agricultural production, the Thao Long Barrage was constructed near the estuarine zone of the Huong River. Although the barrage plays an important role in regional water management, its operation has significantly modified hydrodynamic exchange processes and salinity distributions within the estuarine-lagoon system, potentially affecting aquatic habitats, fish migration pathways, and ecological stability (Bice et al., 2023; Giang et al., 2017).

Therefore, this study develops an integrated hydrodynamic-ecological assessment framework coupling MIKE 11 and MIKE 21 FM models with estuarine ecological analysis to evaluate the impacts of barrage and upstream reservoir operations on the Tam Giang-Cau Hai lagoon ecosystem. The study aims to: 1) quantify spatial and temporal salinity alterations under different barrage operation scenarios; 2) assess rapid salinity transition processes and potential osmotic stress risks for ecologically important indicator species; 3) evaluate the impacts of barrage operation on ecological connectivity and estuarine habitat conditions; and 4) propose eco-adaptive operational strategies for sustainable estuarine barrage management under increasing climate change and freshwater demand pressures.

The novelty of this study lies in integrating hydrodynamic simulations, ecological connectivity analysis, and species-specific salinity tolerance assessment into a unified ecohydraulic framework for evaluating estuarine barrage operations in a tropical lagoon ecosystem. The proposed approach provides a scientific basis for sustainable management of coastal salinity-control structures and environmental flow regulation in tropical estuarine systems across Vietnam and Southeast Asia.

2. Research Methodology

2.1. Selection of a Typical Study Area

To conduct quantitative analyses, the study selected the Huong River basin and the Tam Giang-Cau Hai lagoon system (Thua Thien Hue province) as a typical research model. The Huong River basin covers an area of approximately 2830

km², with a sloping terrain from the western mountainous region to the eastern coastal plain. In the lower reaches of the Huong River, before flowing into the sea, it connects with the Tam Giang-Cau Hai lagoon system, the largest brackish water lagoon system in Southeast Asia, with a surface area of approximately 21,600 hectares and a length stretching along the coastline of 68 km.

The Thao Long Dam, located approximately 8 km upstream from the Thuan An estuary, was completed and put into operation in 2006. At the time of its construction, it was the largest saltwater intrusion prevention dam in Southeast Asia, measuring 600 m in length and comprising 15 regulating bays (each 31.5 m wide) operated by a hydraulic gate system, along with an 8 m wide lock for waterway traffic. The dam's purpose is to prevent the intrusion of saltwater from the East Sea through the lagoon system into the Perfume River during the dry season, to retain freshwater for 39,500 hectares of agricultural land, and to ensure a raw water supply for the Van Nien water treatment plant (28 km from the river mouth) serving the city of Hue. The presence of the Thao Long Dam transforms it into a giant "gateway" that completely controls the exchange of water, suspended matter, and organisms between the Perfume River and the Tam Giang lagoon.

Besides the Thao Long dam, the Huong River system is also strongly influenced by a cascade of large hydroelectric and irrigation reservoirs upstream, including the Ta Trach reservoir on the main river (flood control capacity $W_{pl} = 435.9$ million·m³), the Binh Dien reservoir on the Huu Trach river ($W_{pl} = 156$ million·m³), and the Huong Dien reservoir on the Bo river ($W_{pl} = 150$ million·m³). The operation of water release or storage from these reservoirs directly determines the baseline flow into the Thao Long dam, creating a complex and interconnected system of impacts on the estuary area.

2.2. Data Collection

Salinity and water quality data were collected from two sources:

1) Data used to compare salinity intrusion and water quality fluctuations before and after the construction of the Thao Long dam: Salinity data at sluices and pumping stations along the Huong River are measured and monitored by the Thua Thien Hue Provincial Irrigation Works Management and Exploitation Company to serve water extraction for agricultural production. On the Huong River: data collection points are located 4.75 - 31.5 km from the Thuan An estuary at locations such as upstream and downstream of Thao Long Dam, Ba Sinh, Bao Vinh, La Y, Dap Da, Truong Tien Bridge, and Cau Moi, with fairly frequent measurements; further locations such as Bach Ho, Kim Long, and Thien Mu are also measured, but with significantly fewer measurements; at Quy Lai and Hoa An, the number of measurements is very low, and the data is only for reference... After Thao Long Dam came into operation, measurements in the area upstream of Thao Long Dam almost ceased.

2) Survey data and sample analysis were conducted at 24 points on the Huong River and Tam Giang lagoon by this study in 2024-2025 at different dam opera-

tion times to assess actual saltwater intrusion, salinity distribution, and to provide input for the mathematical model. Both salinity and water quality parameters were measured directly at the field and analyzed in the laboratory.

Ecological data and information were also collected from two sources:

1) Information on characteristic species and ecological features of the estuary area was collected through interviews and direct surveys of local people and authorities.

2) This study also combined field sampling at 24 points on the Huong River and Tam Giang lagoon at different times when the Thao Long dam was open and closed in 2024-2025 to determine the diversity and quantify the abundance of several aquatic plant and animal species through laboratory sample analysis.

2.3. Setting up Mathematical Modeling Tools

The study used the MIKE model suite (Danish Hydraulic Institute), including the MIKE-NAM, MIKE11, and MIKE21FM modules, to calculate inflow, simulate flow regimes, and determine salinity distribution in the downstream area of the Huong River, encompassing the upstream section of the Huong River and the Tam Giang lagoon downstream, under different scenarios.

a) *Scope of research:*

The Huong - O Lau river basin and its tributaries flow directly into the Tam Giang-Cau Hai lagoon system, then empty into the sea at Thuan An and Tu Hien estuaries, including:

- The main course of the Perfume River: From Tuan Junction to Tan My (flowing into Tam Giang Lagoon), including the branches Ta Trach, Huu Trach, and Bo River.
- Rivers in the plains north of the Perfume River and south of the Perfume River.
- Rivers in the delta region south of the Bo River and north of the Huong River.
- Rivers that flow directly into Tam Giang and Cau Hai lagoons, such as the Truoi River, Cau Hai River, and O Lau River, flow into Tam Giang lagoon at Cua Lac.
- The upper boundary of the model ($Q \sim t$): on the Ta Trach River at Duong Hoa, the Huu Trach River at Binh Dien, the Bo River at Co Bi, the Truoi River downstream of the Truoi Dam, the O Lau River at Pho Trach Bridge, the Thac Ma River at My Chanh Bridge, the Cau Nhi River at Cau Nhi Bridge (**Figure 1**).
- The lower boundary of the model is the water level process $Z = f(t)$ at the river mouths and lagoons connecting to the sea, including Tam Giang lagoon at Thuan An estuary and Cau Hai bay at Tu Hien estuary (**Figure 1**).

The MIKE 11 model was validated and calibrated by the flooding events of the year 1983 and 2022 (**Figure 2** and **Figure 3**).

Cross-sectional data of the Huong River and lagoon area were collected from topographic surveying projects in the region (conducted by Ministry of Agriculture and Rural Development and by Thua Thien Hue Province), including 300

river cross-sections and 56 lagoon cross-sections surveyed in 2020, with further updates in 2023.

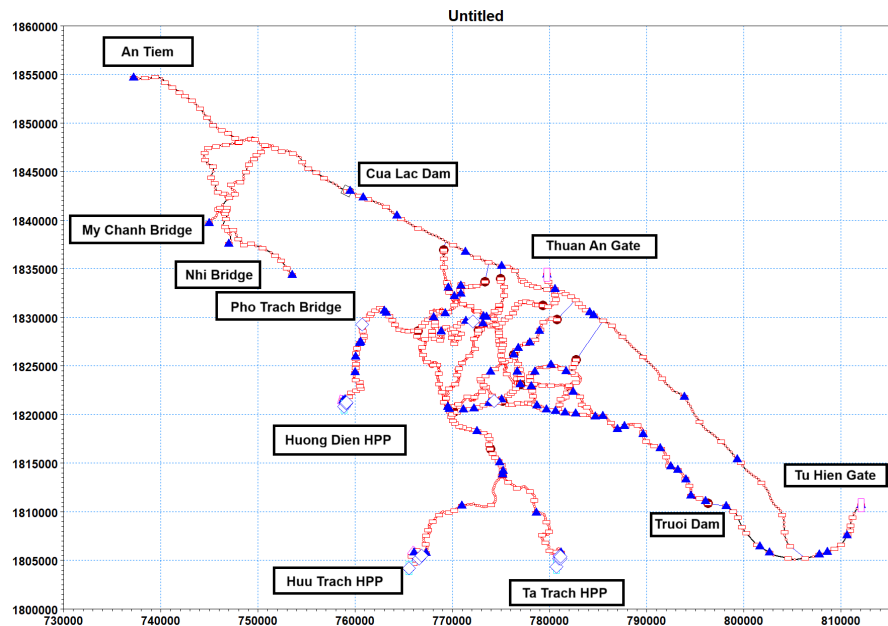


Figure 1. MIKE11 hydraulic calculation diagram.

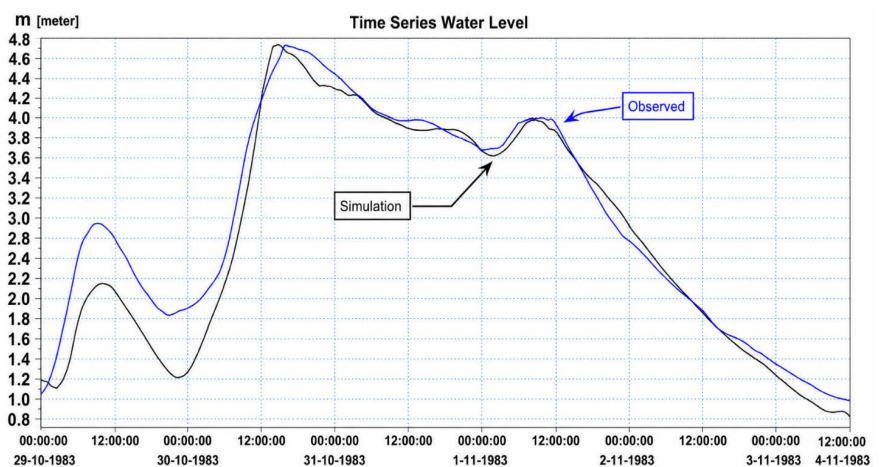


Figure 2. Water level curve simulating the 1983 flood at Kim Long TV station on the Huong River (Location: Huong 13873).

b) *Setting up, calibrating, and testing the MIKE 21 model*

The computational scope of the 2D MIKE21 model covers the area from downstream of the Thao Long dam to the entire Tam Giang-Cau Hai lagoon system (**Figure 4**).

In this model, the upper boundary is connected to the MIKE 11 model, and the 2D model boundary extends from the Truong Giang River area from O Lau to Tam Giang Lagoon and ends at the Cau Hai Lagoon area.

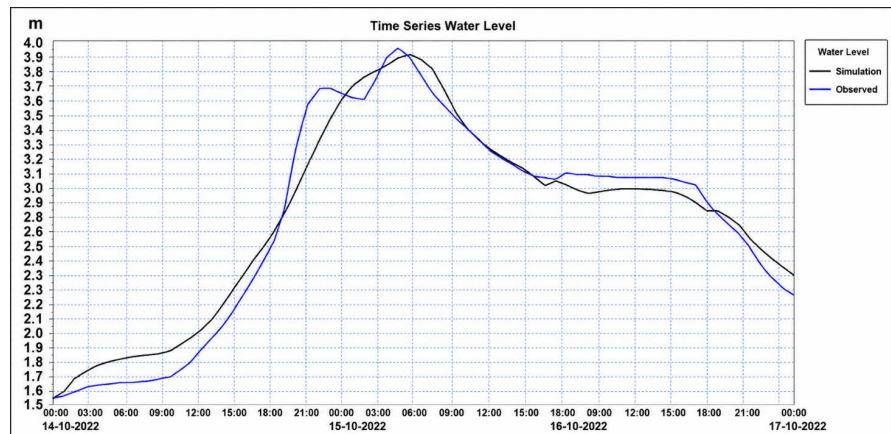


Figure 3. Water level curve for flood verification in October 2022 at Kim Long TV station on Huong River (Location: Huong 13873).

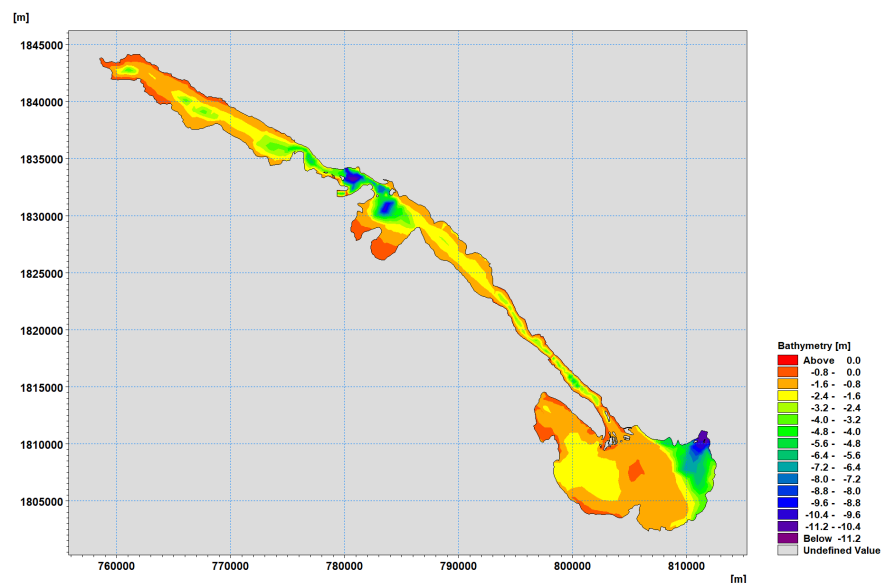


Figure 4. Scope of the MIKE 21 two-dimensional model study.

Bathymetry data and mesh generator: This study utilizes the Mesh Generator module of MIKE 21FM, allowing for the combination of triangular and quadrilateral meshes. The dam structure, sluice gates, water discharge, infrastructure, and important traffic routes were selected for simulation using a quadrilateral mesh to achieve the most realistic representation. After mesh generation, elevation values for the mesh were interpolated from the input data, which included topographic data collected from the aforementioned measured cross-sections and elevation DEM data.

c) Setting up the MIKE FLOOD model

The MIKE 21 model and the MIKE 11 model are connected to each other via a river axis connection and a standard connection.

Standard connection along the river axis: This is a standard connection in MIKE FLOOD, where one or more MIKE 21 cells/elements are linked to the end

point of the MIKE 11 river branch (Table 1).

Table 1. Statistics of boundary connections in the MIKE FLOOD model.

Connection Type	River Name	Connection Location	Number of Connected Molecules
Standard	Ha Do	158,108	16
Standard	Bo An Xuan	45,080	16
Standard	Crab Restaurant	38,556	16
Standard	Huong	24,756	16
Standard	La Y	19,972	16
Standard	twin dragons	9020	16
Standard	Dai Giang	2930	16

d) *Result of the water level and discharge calibration*

Water level and discharge calibration results are shown in Figure 5.

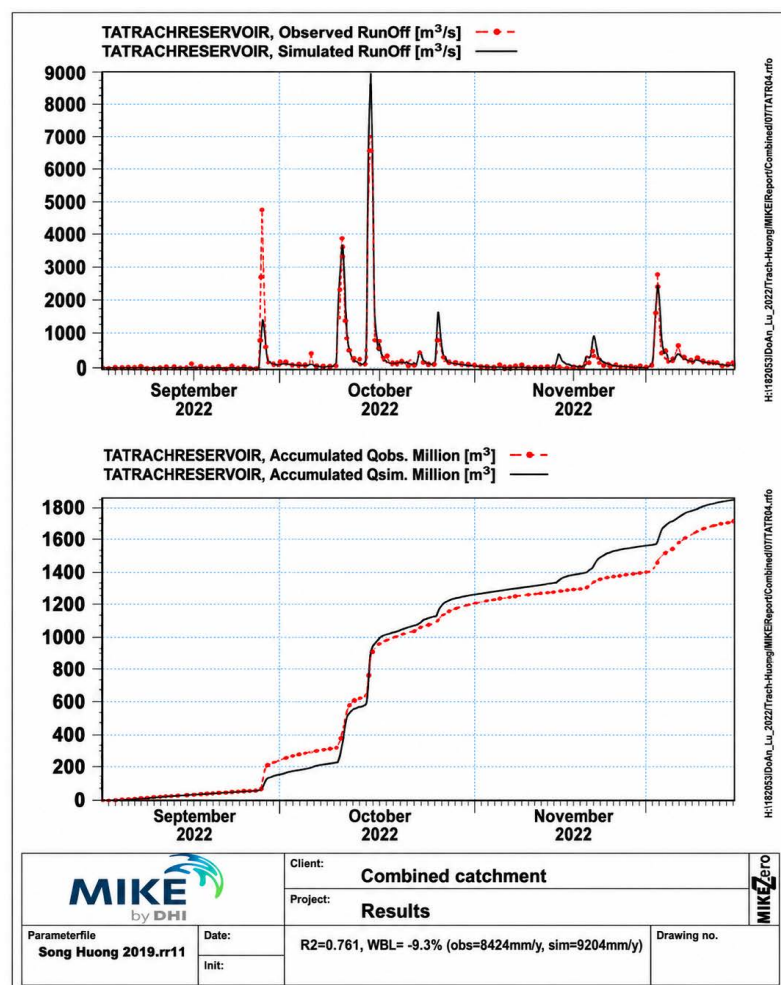


Figure 5. Results of the 2022 flood flow calibration at Ta Trach Reservoir.

e) *Simulation results of the salinity calculation model***Table 2.** Comparison of results between the model and additional measurement stations in 2024.

No.	Measurement Station	Maximum Salt Content (g/l)		Minimum Salinity (g/l)		Difference	
		Actual Measurement	Model	Actual Measurement	Model	Maximum (g/l)	Minimum (g/l)
1	TV1	13.08	12.59	3.18	4.00	0.49	0.82
2	TV2	1.40	1.32	0.63	1.03	0.08	0.40
3	TV3	1.03	1.02	0.50	0.73	0.01	0.23
4	TV4	0.92	0.92	0.31	0.55	0.00	0.24
5	TV5	0.79	0.82	0.40	0.41	0.03	0.01

Salinity simulation results show that the errors in peak amplitude and phase compared to the actual measured data do not differ significantly and are within acceptable limits, making the parameters reliable for the model simulation (**Table 2**).

f) *Model calibration and validation*

Indicators for evaluating the reliability of mathematical modeling tools are shown in **Table 3** below.

Table 3. Summary of indicators for evaluating the reliability of mathematical modeling tools.

Planet	Station	NSE	RMSE	R ²	Performance
Water level	Kim Long	0.91	0.08 m	0.93	Excellent
Salinity	Thuan An	0.82	1.7‰	0.85	Good
Discharge	Co Bi	0.79	5.6 m ³ /s	0.81	Good

2.4. Characteristics of the Ecological Diversity of the Huong River Estuary and Tam Giang Lagoon

Like other coastal estuaries, the Huong River estuary (**Figure 6**) is characterized by very high biodiversity. Particularly in the area outside the estuary bordering the sea, there is a large lagoon where there is a constant exchange of saltwater and freshwater, resulting in the discovery of many aquatic plant and animal species in a rich ecosystem.

Based on the collected information and sample analysis, the main characteristics of the aquatic flora and fauna in the study area can be identified as follows:

a) *Fish*

- Regarding fish eggs and juveniles, the study area identified fish eggs and juveniles of 50 fish species belonging to 34 families, 46 genera, and 8 orders.
- Regarding the density of fish eggs, survey results in the study area show that the area has an average of about 240 fish eggs/1000 m³ of surface water and about 490 juvenile fish/1000 m³ of surface water.

- 164 fish species were identified, with the Perciformes order being the most dominant, comprising 110 species, accounting for 63.95% of the total species found in the study area.
- Fourteen orders and 59 families of fish were identified during the survey and analysis of specimens in the study area. The Perciformes order was dominant in terms of the number of families, genera, and species (over 50%).

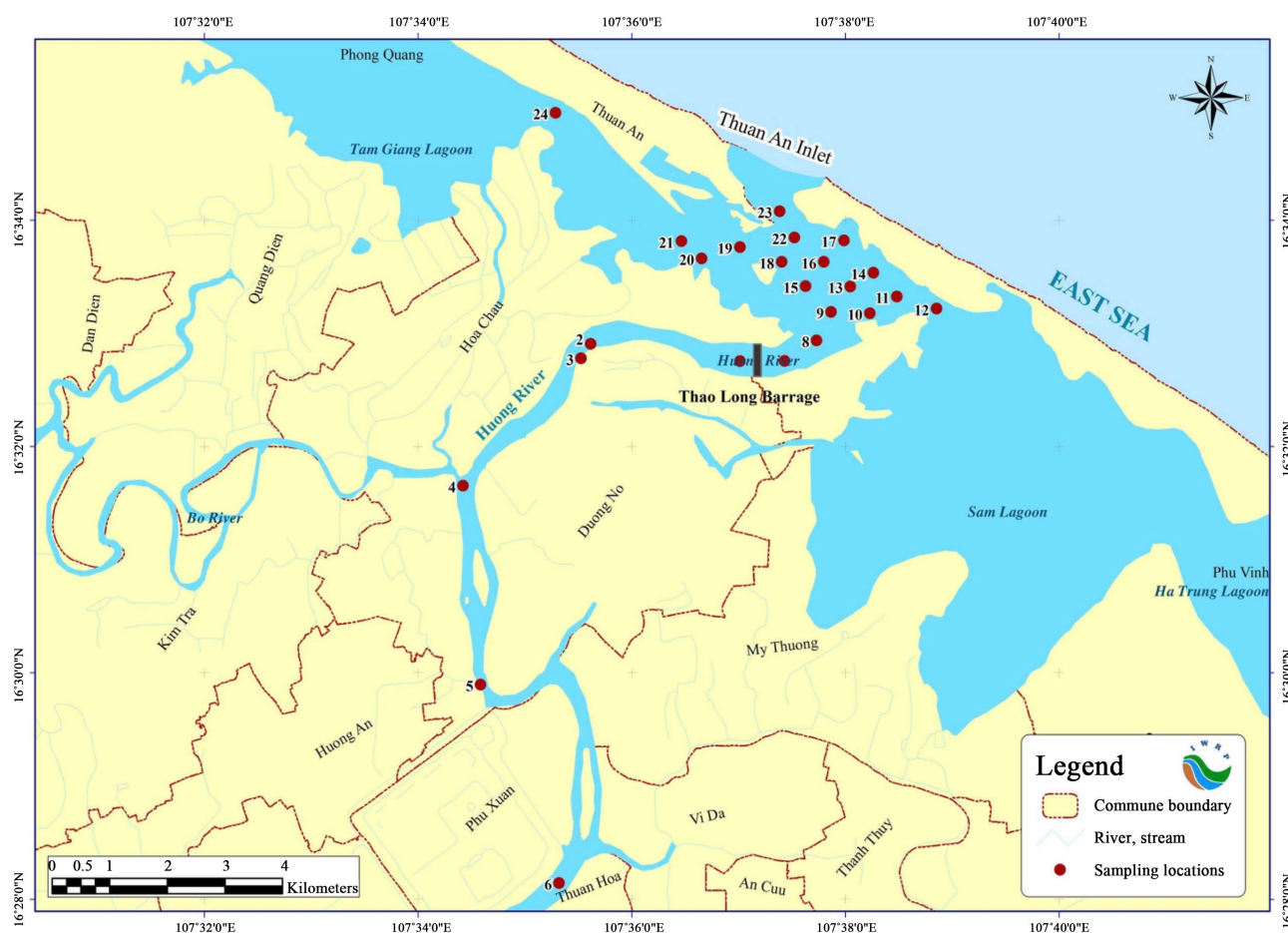


Figure 6. Map of ecological sampling locations.

Some of the most distinctive native fish species include:

- Rabbitfish (*Siganus guttatus*): This is a common species, both caught in the wild and widely raised in ponds/cages.
- Gold-spotted Spinefoot (*Siganus canaliculatus*): A famous endemic species of Tam Giang Lagoon, living in estuary and lagoon areas.
- Terapon fish: Naturally found in estuaries (lower reaches of the Perfume River) and lagoons.
- Sea Bass (Barramundi/Sea Bass-Lates calcarifer): Naturally distributed and raised intensively or semi-intensively.
- Red Drum (*Sciaenops ocellatus*): An introduced species, now widely farmed in Tam Giang lagoon due to its good disease resistance.

- Brown Catfish (*Scatophagus argus*): found in the wild and raised in polyculture with shrimp or in monoculture.

b) *Floating plants*

- 79 species of phytoplankton/algae were recorded in the collected water samples. Of these, Sample Group 4 had the highest number of species (36 species), followed by Sample Group 3 (28 species); Sample Group 1 (27 species), then Sample Group 5 (22 species); Sample Group 2 (17 species) and finally Sample Group 6 (15 species). One common species, *Cyclotella* sp., was found across all 6 water samples, indicating differences in water quality at the 6 sampling points.
- Sample Group 4 recorded 13 species; followed by Sample Group 1 - 12 species; Sample Group 5 - 8 species; Sample Group 6 and Sample Group 3 - 6 species each; and finally Sample Group 2 - 1 species. Water quality at the 6 sampling points varied considerably.
- The diversity index (H') at the 6 sampling points varied from 2.71 to 3.32, all greater than 2.5, indicating that the water at the sampling points was relatively clean and of good quality. Water samples from Group 2 had the highest nutrient content, followed by Group 6, Group 5, Group 1, Group 3, and finally Group 4 had the lowest nutrient content.
- The highest similarity coefficient for microalgal species composition was between samples Group 6 and Group 5 (0.72222); the lowest was between samples Group 4 and Group 3 (0.39286).
- The microalgal populations of the Downstream Shore sample and Group 5 are very similar. Next, these two microalgal populations are more closely related to the Group 2 sample, followed by the Group 4 sample. These samples then show differences compared to the Group 1 sample. Finally, the Group 3 sample is noted to have a distinctly different microalgal population structure compared to all five other samples.
- Environmental salinity and pH had no effect on either the species composition or cell density in the 6 water samples. Salinity did not correlate with or affect the number of species or cell density because its Sig. value was greater than 0.05.

c) *Floating animals*

- Twenty-six species of zooplankton have been identified, including representative species found in coastal estuaries, and dominant species in freshwater and brackish water environments. Species diversity is not high, with a limited number of species. Four species were found at most of the study sites and groups of sites: *Schmackeria gordioides*; *Oithona simplex*; *Euterpina acutifrons*, and crustacean larvae: Crustacea.

d) *Other characteristic species that are strongly affected by salinity include:*

- The Tria (Sea clam/Brackish water clam - *Corbula* sp.): is the most famous and endemic bivalve mollusk of the Tam Giang region. Living buried in the muddy, sandy bottom and moving very little, it cannot escape sudden envi-

ronmental changes.

- *Metapenaeus ensis* (also known as freshwater shrimp): This is a naturally occurring shrimp species with a sweet taste and thin shell, and is the main ingredient in Hue-style fermented shrimp. Although euryhaline, its reproductive and molting cycles are highly dependent on salinity.
- Seagrass and Gracilaria: These serve as “nursery homes” for shrimp and fish larvae and as food for barramundi and whale fish. Gracilaria only thrives in brackish water.

2.5. Develop Operating Scenarios for Dams and Reservoir Discharges

The study developed numerous computational scenarios. Of which, six typical scenarios for the operating states of Thao Long dam opening and closing and water discharge from the upstream reservoirs were selected for analysis here. Water sources conditions and natural salinity patterns are based on data collected in 2020, a typical year of drought, saltwater intrusion, and extreme water shortages:

- **Scenario VH1: Dry-season operation (January to August)**
 - Dam operated according to dry-season regulations.
 - Reservoir discharge followed hydropower operation schedules.
 - Maximum water discharged through the dam, when it is opened, from 200 to 400 m³/s. However, the time of dam opening were limited.
- **Scenario VH2: Flood-season operation (September to December)**
 - Dam gates opened for flood release.
 - Reservoirs discharged according to inter-reservoir flood operation rules.
 - Maximum water discharged through the dam from 400 to 600 m³/s.
- **Scenario VH3: Large upstream release with dam opening (August to October)**
 - Full dam opening.
 - High reservoir discharge during flood season.
 - Maximum of total flood water discharged from three upstream reservoirs about 3,500 to 4,000 m³/s.
- **Scenario VH4: Large upstream release with dam closure (August to October)**
 - Dam completely closed.
 - High upstream reservoir discharge.
 - Flood water released from upstream reservoirs was set similar to scenario VH3.
- **Scenario VH5: No reservoir release with dam opening (January to April)**
 - Dam fully open.
 - Reservoir discharge set to zero.
- **Scenario VH6: No reservoir release with dam closure (January to April)**
 - Dam fully closed.
 - Reservoir discharge set to zero.

2.6. Conceptual Ecohydraulic Assessment Framework

The integrated assessment framework developed in this study consists of four interconnected components:

- 1) hydrological and hydrodynamic simulation using MIKE 11 and MIKE 21 FM;
- 2) salinity alteration assessment under different dam operational scenarios;
- 3) ecological response analysis based on species-specific salinity tolerance thresholds and ecological connectivity indicators;
- 4) eco-adaptive operational evaluation for minimizing ecological disturbances while maintaining freshwater regulation objectives.

The framework links hydrodynamic drivers with ecological processes through salinity transition dynamics, thereby allowing quantitative assessment of ecological risks associated with dam operation.

3. Results and Discussion

3.1. Salinity Fluctuations and Saltwater Intrusion Potential

Before the dam was built (before 2006), during the dry season months from April to August, saltwater intrusion occurred freely in an irregular semi-diurnal tidal regime, penetrating tens of kilometers inland. Salinity measured at the Kim Long station (19 km from the river mouth) reached 8.6‰ and at the Thuy Bieu pumping station (28 km away) was 4.7‰, far exceeding the 1‰ threshold permissible for agricultural irrigation.

During the dam's construction, analysis of the VH6 scenario (no reservoir discharge, dam closed) showed that the Thao Long dam successfully prevented saltwater intrusion. As shown in **Figure 7**, at the upstream area near the sluice gate, salinity levels remained stable below 0.5‰ (ensuring the safety of the Van Nien water treatment plant supplying Hue City). However, the salinity boundary in the lagoon immediately downstream of the dam experienced a localized increase in salinity due to the reduction in freshwater flow, combined with the high evaporation rate of the dry season. This transformed the downstream section of the river and the head of the Tam Giang lagoon into a saltwater zone, altering the spatial structure of the brackish water environment.

Simulations show similarities to the phenomenon observed at the Brisbane estuary (Australia), where maintaining estuarine salinity below 1‰ requires a continuous environmental discharge rate of 150 - 175 m³/s (Khalil et al., 2025). In the Huong River, due to water retention in reservoirs (VH5, VH6 scenarios), the discharge rate through the dams is almost zero, prolonging the salinity equilibrium time for the entire lagoon system.

3.2. Water Quality Deteriorates Due to Stagnation

The closure of the dam (scenarios VH1 during most of the dry season, VH4 and VH6) creates a prolonged period of still water, reducing the flow velocity to negligible levels, eliminating the kinetic energy necessary for self-purification and di-

lution of organic pollutants discharged from residential and agricultural areas on both banks.

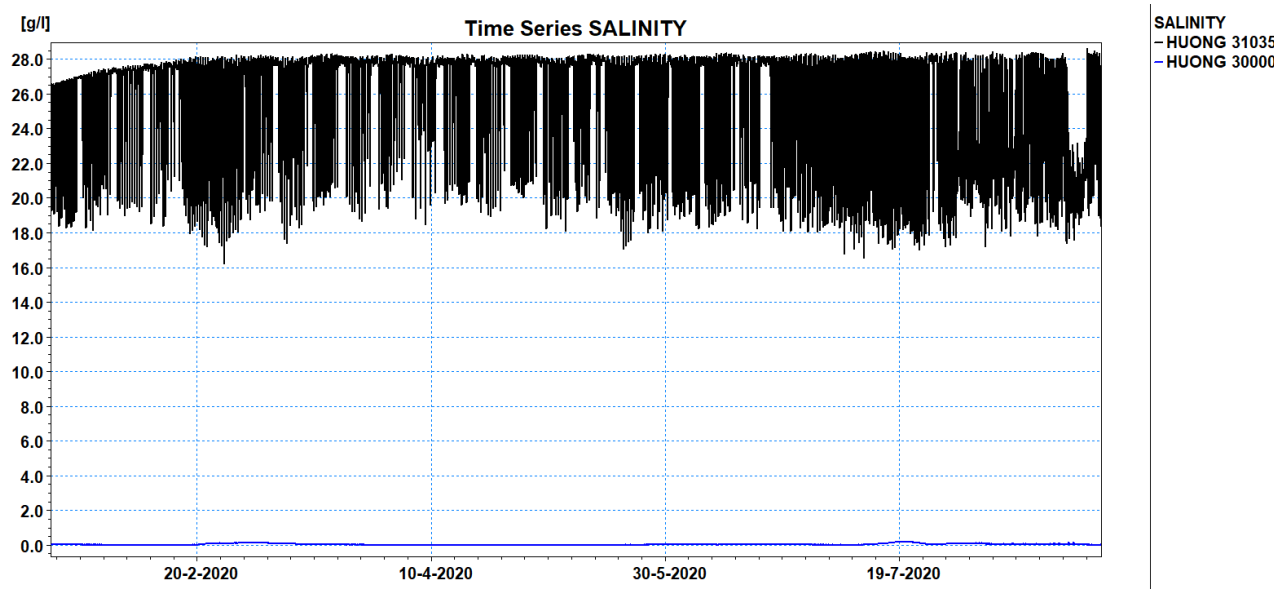


Figure 7. Salinity upstream and downstream of Thao Long dam when the dam is completely closed during the dry season.

Analysis of long-term monitoring data before and after 2006 (when the Thao Long dam became operational) and monitoring data from 2024-2025 along the main channel of the Huong River reveals significant changes:

Dissolved oxygen (DO): The average DO content showed a slight decrease (from 7.04 mg/l to 5.24 mg/l). The slow flow rate reduced the natural aeration capacity at the surface, combined with the decomposition of organic compounds sinking to the bottom, consuming a large amount of oxygen.

BOD₅ and COD: The impact of the dam has turned the upstream area into a collection point. Although the biochemical oxygen demand (BOD₅) and chemical oxygen demand (COD) levels remain under control below the A1 standard of QCVN 08-MT:2015/BTNMT (due to the relatively clean water in the Huong River basin), significant differences have been observed compared to free-flowing sections of the river. Typically, the BOD₅ value measured in the tributaries reached as high as 7.97 mg/l due to wastewater not being able to drain into the river mouth.

Eutrophication risk: The phosphate (PO_4^{3-}) concentration near the dam was recorded at 0.008 mg/l, approaching the eutrophication risk threshold (0.01 mg/l). When the sluice gates are continuously closed for many months, temperature stratification and nutrient concentration cause a sudden increase in total Coliform density, stimulating the outbreak of microalgal populations and threatening the water ecosystem.

3.3. Sudden Impacts of “Salt Shock” and “Freshwater Shock”

- Under scenario VH2, when operating the dam normally, while the highest sa-

linity at the Thuan An estuary remains at approximately 29‰, the salinity in the lagoon fluctuates in both value and distribution range. Salinity in the area immediately downstream of the dam decreases to about 7‰, and in the central lagoon area it only fluctuates between 7‰ and 10‰ (Figure 8). Notably, the freshwater intrusion affects the lagoon's edge near the Thuan An bridge, impacting aquaculture areas there.

- Scenarios VH3 and VH2 at certain times: When operating the reservoir's flood discharge and opening the dam, salinity in the central lagoon area decreases to 5‰ - 8‰, with a distribution range covering almost the entire area from downstream of the dam to the center of the lagoon, clearly distributed according to the direction and range of flow from upstream through the dam into the lagoon.

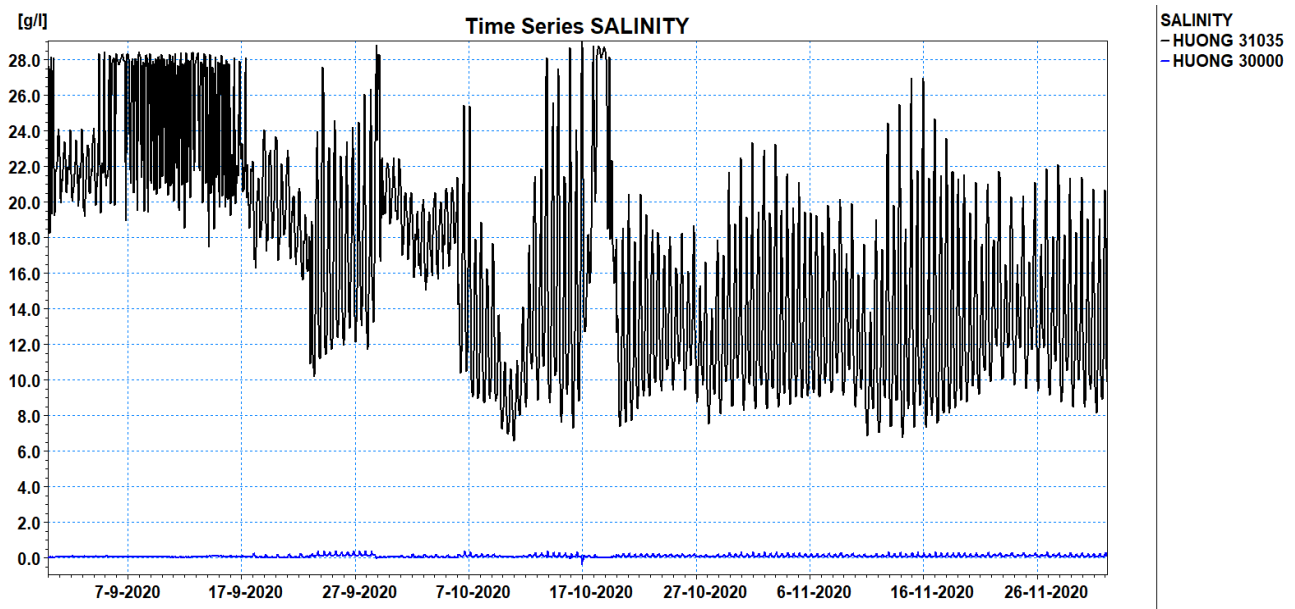


Figure 8. Salinity upstream and downstream of Thao Long dam when the dam is fully opened during the flood season.

Simulation results using a 2D model show that in the case of closing the Thao Long dam, the distribution of flow direction and velocity in the lagoon completely depends on the tidal activity through the Thuan An estuary. The largest flow fluctuates in the lagoon estuary area and from both the left and right sides of the lagoon, concentrating in the central area, with the highest velocity ranging from 0.6 m/s to 0.8 m/s during high tide and from 0.45 m/s to 0.65 m/s during low tide (Figure 9). Meanwhile, in the area near the downstream of the Thao Long dam, the flow velocity is always very low, below 0.2 m/s, due to the impact of the dam.

Conversely, when the dam is opened and the reservoir is discharged, the flow velocity in the downstream area of the dam increases significantly, reaching 0.4 m/s to 0.55 m/s in the direction of flow through the dam into the lagoon. The impact extends to the central area of the lagoon (Figure 10).

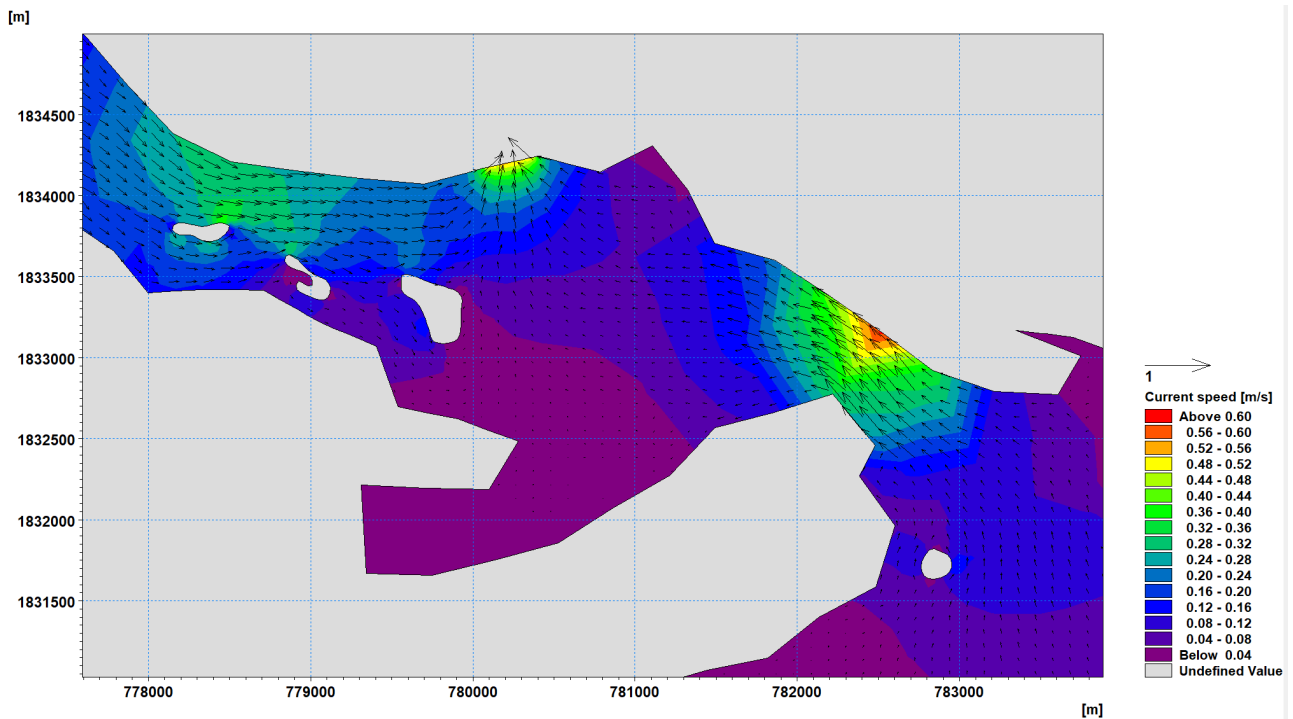


Figure 9. Velocity distribution at Tam Giang Lagoon during low tide and dam closure.

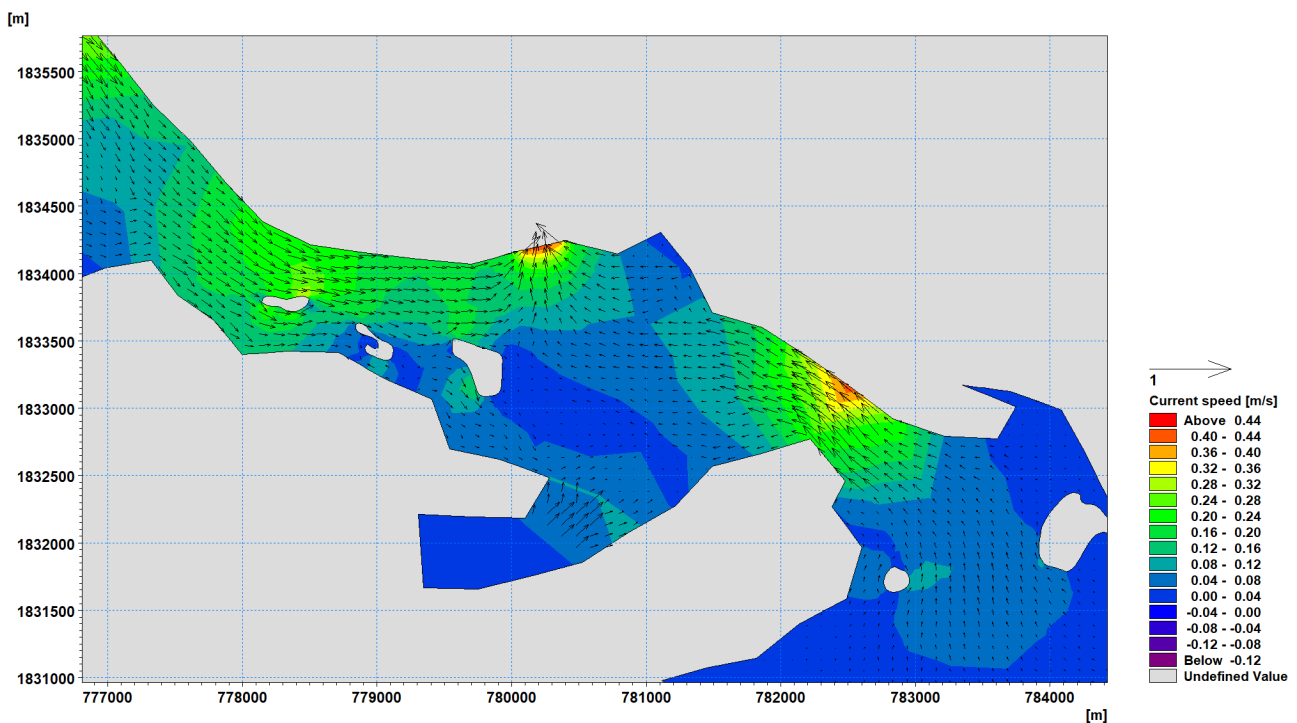


Figure 10. Velocity distribution at Tam Giang Lagoon during low tide and with reservoir operation and dam opening.

The distribution pattern of flow direction and velocity described above greatly influences salinity distribution, specifically the potential for freshwater intrusion into the lagoon area when water is released through the dam.

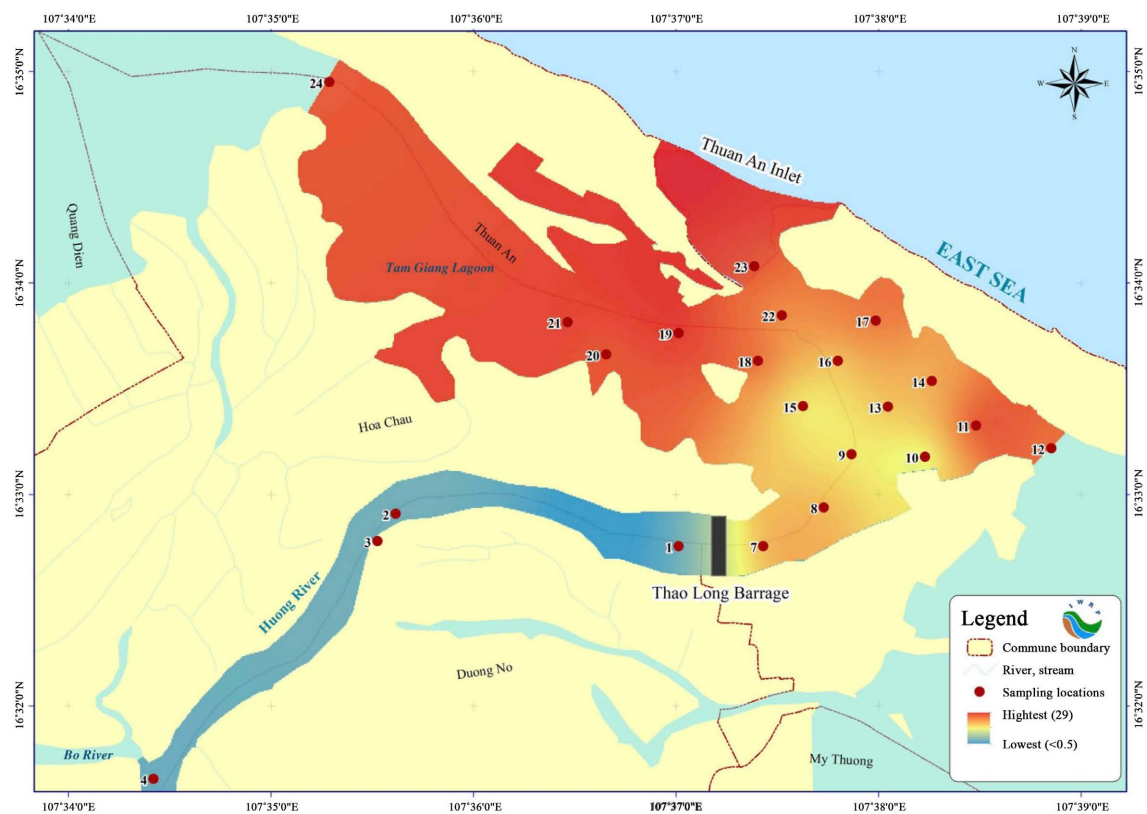


Figure 11. Salinity distribution in the Tam Giang Lagoon area during normal dam operation.

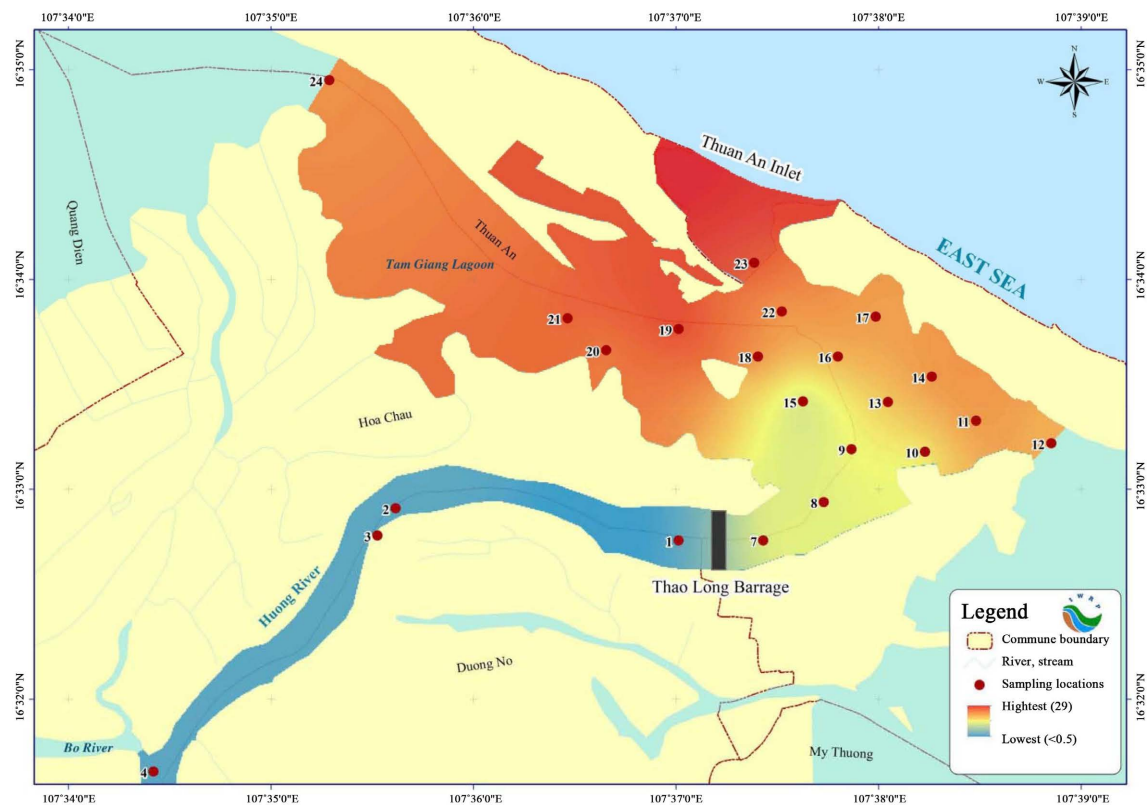


Figure 12. Salinity distribution in the Tam Giang Lagoon area during flood discharge and dam opening operations.

When operating the reservoir's floodgates and opening the dam, the salinity reduction range in the lagoon is expanded, extending to the outer coastal areas where it is only 20‰ to 22‰, and at Thuan An estuary it is about 28‰. Salinity in the central lagoon area decreases to 5‰ - 8‰, with a distribution range covering almost the entire area from downstream of the dam to the center of the lagoon, clearly distributed according to the direction and range of flow from upstream through the dam into the lagoon (**Figure 11**).

After a long period of salinization in the lagoon (over 20‰ - 25‰), opening the dam to release a large amount of water from the Huong River (**Figure 12**) will cause the salinity in the downstream area to drop to 5‰ within just 24 - 48 hours. This process far exceeds the osmotic pressure regulation capacity of the species, causing adverse ecological impacts on the structure of the flora and fauna (**Table 4**).

Table 4. Summary of extreme physiological responses of indicator species in the area corresponding to salinity fluctuations.

Name of Aquatic Species	Ecological Characteristics & OSMOTIC Physiology	Survival/Optimal Salinity Threshold	Physiological Response to Sudden Water Release through the Dam (Freshwater Desalination)
Spotted scat (<i>Scatophagus argus</i>)	This euryhaline species lives in estuaries. Its genome contains diverse COI. Ion regulation across the gills is achieved through the Na ⁺ -K ⁺ -ATPase (NKA) pump and the cotransporter protein NKCC1.	Very wide range: 5‰ - 35‰. Maximum growth in brackish water.	Hypotonic shock below 5‰ inhibits NKCC1 expression. Fish are forced to expend ATP to pump back ions, drastically reducing the O:N ratio, leading to stunted growth, malnutrition, and increased susceptibility to disease.
Rabbitfish (<i>Siganus canaliculatus</i> , <i>S. guttatus</i>)	They depend on estuaries as hatching grounds. The larvae are highly sensitive to light and salinity. They migrate according to the first lunar cycle.	Optimal range: 20‰ - 32‰. Tolerance of narrow variation (±5‰).	The hatching rate drops drastically when salinity is below 20‰. A sudden drop in salinity causes mass larval mortality due to the cells losing their ability to maintain pressure, leading to rupture of the mucous membrane.
Native clams/Tria (<i>Corbula sp.</i>)	Benthic animals, bivalve mollusks. They are fixed in place under mud and sand, have large biomasses, and naturally filter water for organic matter.	Optimal salinity: 15‰ - 25‰. Highly sensitive to freshwater.	When the salinity drops below 5‰, it causes osmotic shock. The clams completely close their shells, ceasing respiration and feeding. This lasts 3 - 5 days, leading to mass mortality and decomposition that contaminates the seabed.

Continued

Shrimp (<i>Metapenaeus ensis</i>)	Crustaceans have high domestic commercial value. Their growth process depends on molting cycles that extract ions from the environment.	Brackish lagoon water. Sensitive to mineral concentrations.	A decrease in salinity stimulates forced molting in shrimp. However, excessively fresh water and a lack of minerals prevent shrimp from regenerating their shells (resulting in soft shell syndrome), leading to exhaustion and predation.
Seaweed (<i>Gracilaria</i>) and Seagrass	Aquatic plants provide primary productivity, acting as “ecological nurseries,” supplying food for fish.	Optimal salinity: 15‰ - 20‰. Growth salinity: 5‰ - 30‰.	Freshwater floods carry high turbidity (reducing photosynthesis), and combined with freshwater shock, cause algal cells to swell and cell walls to rupture. The algae become “white-tipped,” rot, and their entire food web collapses.

Furthermore, the prolonged closure of dams also reduces the ability to regulate salinity, leading to increased salinity in the lagoon area, with a tendency towards accumulation. Statistical data on biodiversity from similar systems, such as the study at Baffin Bay (Texas) when estuarine salinity reached high levels, showed a shrinking of ecological “hotspots” and a significant decline in species richness (Ethan & Catherine, 2022).

3.4. Disruption of Migration Routes and Ecological Disconnection

The operation of dam closures (operational scenarios VH4, VH6 and the closure times of VH1) will prevent the migration of bivalve fish species, which need to move freely between marine and freshwater environments to complete their life cycle (reproduction, feeding, shelter). This disruption of connectivity has resulted in a 73% decline in the global population of migratory fish species since 1970 (Bice et al., 2023).

In the Tam Giang-Cau Hai lagoon, the species most directly affected is the Siamese fighting fish (*Siganus canaliculatus*), a commercially valuable species for 90% of aquaculture facilities along the lagoon, which are entirely dependent on natural fish stocks. Population ecology studies indicate that the migration patterns of Siamese fighting fish larvae from the open sea through the Thuan An estuary into the lagoon are tightly programmed by the lunar cycle. The strongest migrations and highest concentrations of juvenile fish occur during the first quarter moons from April to November, with peak catches reaching up to 370 kg per net haul, followed by a sharp decline during the full moon (Giang et al., 2017).

In addition, several common fish species (Table 3) with migratory and spawning habits between rivers and estuaries, and in the sea, such as eels (Jéhannin et al., 2022), bidirectional migratory gobies (Le & Nguyen, 2020), mullet (Able, 2005), snapper, and amberjack (Nagelkerken et al., 2000)... are also greatly affected in

terms of their reproductive capacity, development, and diversity in species and numbers (**Table 5**).

Table 5. Migratory characteristics of some native fish species.

TT	Species	Migration and Reproduction Patterns
1	Eel (<i>Anguilla marmorata</i>)	They live in freshwater/inland waters, then migrate to the sea to breed; the young migrate upstream into rivers/estuaries.
2	Gobies migrate in both directions (e.g., species belonging to the Gobiidae/Sicydiinae group).	Young fish return to the river/stream estuary, and adults can either migrate to the sea or upstream; they depend on small coastal river/stream estuaries to complete their life cycle.
3	Mullet (Mugilidae)	Fish breed in the open sea or coastal areas; juvenile and young fish use estuaries/brackish water/river mouths as nurseries/feeding grounds before growing.
4	Some marine species are dependent on estuaries (e.g., sea bass, scad, snapper, amberjack, etc.).	Breeding occurs far from the mouth of the river, but the fry/larvae need brackish water/estuaries/lagoons as nursery areas.
5	Native freshwater/brackish water species that tolerate moderate salinity (e.g., snakehead fish, catfish, native tilapia, etc.)	They don't need long migrations, can survive in brackish water environments, and sometimes invade estuaries/estuary areas when salinity is suitable.

Furthermore, when the Thao Long dam operates with its sluice gates closed during the dry months, it eliminates the exchange of nearshore ocean currents, inhibiting the “olfactory signals” from freshwater discharges into the sea—which serve as a compass for juvenile fish to navigate into the estuary. The dam closure separates parent fish from spawning grounds and prevents juveniles from accessing the seagrass “nursery” habitat inside the lagoon, leading to population shrinkage and a decline in genetic diversity (Bice et al., 2023; Van Nguyen et al., 2022).

The combined impact of the Thao Long dam's operating conditions on the migration and breeding habits of common fish species is summarized in **Table 6**.

3.5. Several Integrated Environmental Engineering and Management Solutions

These scientifically and practically grounded findings indicate the need to shift the operating principles of salinity control dams like the Thao Long dam from “absolute containment” to “ecological adaptation and regulation,” coordinating harmoniously with the upstream reservoir system. Only when operating procedures are redesigned based on the rhythm of nature—releasing small flows, following the weak tidal cycle, synchronizing the upstream reservoir chain, and ensuring environmental flow—will salinity control dams truly become sustainable tools, meeting both the socio-economic development needs of people and protecting the estuarine, lagoon, and coastal ecosystems.

Table 6. Impacts of dam operation on fish species.

Time	Status of Thao Long Dam	Fish Migratory Behavior	Level of Impact & Consequences
February-April (Spring)	Almost completely closed (To prevent saltwater intrusion and retain freshwater for irrigating the winter-spring rice crop).	Peak upstream migration: - Sardines: Migrating upstream to spawn. - Freshwater eel (baby): Swims from the sea into the river. - Juvenile sea bass: They migrate to estuary areas to live.	- Sardines cannot enter the river to lay eggs. - The chicks couldn't get upstream to replenish the herd. - Fishermen are engaging in destructive fishing practices that deplete fish stocks concentrated in the dam area.
May-August (Summer)	Close or Open restrictions (depending on drought/salinity intrusion)	Development stage: - Young fish need calm, food-rich waters in estuaries. - River fish species (carp, tilapia) migrate to slightly brackish water areas to feed.	- The upstream environment of the dam becomes stagnant, polluted, and lacks oxygen, killing fish eggs and fry. - Disruption and loss of nutrient exchange between the river and the lagoon.
September-December (Flood Season)	Fully open, with occasional large-scale flood releases from upstream reservoirs.	Downstream migration: - Female eels: They migrate downstream to the sea to lay their eggs. - Fish in the lagoon seek shelter from strong currents.	- Excessively strong currents (due to concentrated flood discharge) sweep weaker fish out to sea too quickly, causing salinity shock. - Accelerates and disrupts the natural migration of species to the sea.

Based on an analysis of damage to the physical and biological structures, the study recommends a shift in dam operation, moving from “absolute containment” to “ecological adaptation regulation”:

1) Applying Controlled Tide Reduction (CRT) Mechanism

The most groundbreaking and feasible technological proposal is to transform existing infrastructure to apply the Controlled Reduced Tide (CRT) mechanism. The CRT mechanism has been thoroughly studied and proven highly effective in numerous large-scale estuary restoration projects in Europe, notably the project in the Lippenbroek wetland area along the Scheldt Estuary in Belgium.

In a standard CRT configuration, hydraulic engineering utilizes a structure consisting of a high inlet and a low outlet to extract a small amount of kinetic energy from the spring tide and dead tide amplitudes. By modifying or reconfiguring the opening of some sluice gates at Thao Long according to the CRT principle during the dry season or transitional seasons, managers can allow a defined volume of tidal prism to safely penetrate deep into the downstream river basin. This partial tidal exchange addresses three essential ecological functions:

- Salinity Gradient Restoration: Continuous, rather than static, exchange of seawater and freshwater masses prevents excessive salinity concentration due to evaporation downstream, recreating a smooth salinity gradient instead of a ab-

rupt dividing line.

- Water Pollution Mitigation: The established continuous turbulent flow breaks stagnation, increases dissolved oxygen (DO) concentration through natural aeration, and dilutes the concentration of organic pollutants (BOD₅, COD), eliminating conditions conducive to pathogen growth.
- Open Migration Corridor: A continuous flow through the dam structure supports the passive drift of planktonic larvae and naturally guides young migrating fish back to their wetland habitat.

2) Coordinated Environmental Flow

The role of the Thao Long Dam cannot be separated from the operating regime of the upstream Ta Trach reservoir. To combat hydrodynamic degradation during the dry season, ensuring the maintenance of a continuous Environmental Flow (E-flow) from the Ta Trach dam through Thao Long is a prerequisite. Rapid assessments from international organizations (such as IUCN) and hydraulic simulations all emphasize that a minimum baseline flow of approximately 25 to 31 m³/s at the river mouth is an unavoidable requirement. This flow not only provides a hydroaulic head to flush out acidity from the irrigation canal system but also maintains the necessary pressure to operate the sluice gates according to the CRT model. The timing of opening the sluice gates at Thao Long needs to be calculated synchronously through flow routing steps using MIKE 11 so that the time of water release from the reservoir coincides with the high tide cycle, optimizing the mixing process.

3) Stepwise Gate Protocols to Combat Salinity Shock

To completely eliminate the “freshwater shock” disaster during flood discharge, the traditional binary control mode (only two states: fully closed or fully open) needs to be immediately eliminated and replaced with stepwise gate-opening procedures. Based on meteorological forecasts and early reservoir discharge signals, the radial and flap gates will be gradually opened in small increments several days before the flood peak.

Creating a controlled salinization pathway—for example, reducing salinity from 20‰ to 5‰ over a period of 96 to 120 hours instead of a steep drop in 24 hours—would provide the ecosystem with an invaluable “physiological window.” This would give sensitive species such as *Scatophagus argus* and *Siganus guttatus* larvae sufficient biological time to restructure their cellular chloride systems and accelerate lipid metabolism in response to hyperosmolarity regulation requirements.

4) Adaptive transformation of agriculture and fisheries:

Non-structural measures must be implemented synchronously. The agricultural sector needs to advance the planting schedule for the winter-spring rice crop, using short-day rice varieties to harvest before salinity peaks. For households raising tilapia and other fish in lagoons, it is necessary to establish a flood warning system and recommend harvesting all fish before October-November each year to avoid the risk of freshwater intrusion causing widespread mortality.

3.6. Uncertainty and Limitations

Although the study integrated hydrodynamic modeling with ecological analysis, there are still some limitations that need further improvement:

- 1) measured ecological data do not adequately cover seasonal and multi-year cycles;
- 2) the study has not integrated models of sediment transport and estuary morphology changes;
- 3) The long-term impacts of climate change and sea-level rise have not been modeled in detail;
- 4) The physiological responses of new aquatic species are primarily based on reference thresholds from internationally published literature.

In subsequent studies, it is necessary to integrate ecological dynamics models, water quality models, and long-term climate scenarios to enhance the reliability of the integrated ecological assessment.

4. Conclusion

This study developed an integrated ecohydraulic assessment framework coupling hydrodynamic simulations and estuarine ecological analysis to evaluate the impacts of dam and upstream reservoir operations on the Tam Giang-Cau Hai estuarine lagoon system. The coupled MIKE 11 – MIKE 21 FM modeling system successfully simulated hydrodynamic processes, water level fluctuations, and salinity distributions under different operational scenarios of the Thao Long dam.

The results indicate that prolonged dam closure during the dry season significantly increases flow stagnation, reduces hydrodynamic exchange between riverine and marine systems, and intensifies salinity accumulation within the lagoon. In contrast, sudden gate opening combined with upstream reservoir flood releases generates rapid salinity declines exceeding the physiological adaptation capacity of many estuarine organisms. Such “freshwater shock” processes were identified as major drivers of osmotic stress, ecological disturbance, and habitat degradation for key indicator species.

The study further demonstrates that dam operation not only alters hydrological and salinity regimes but also disrupts ecological connectivity between riverine, estuarine, and marine environments. Long-term closure conditions interrupt migratory pathways, reduce larval transport processes, and weaken ecological exchange mechanisms, thereby threatening biodiversity and ecosystem functions within the lagoon system.

Based on the hydrodynamic and ecological assessment results, the study highlights the necessity of shifting from conventional “absolute salinity exclusion” strategies toward eco-adaptive dam operation approaches. Such approaches should incorporate environmental flow maintenance, controlled salinity transition rates, enhanced tidal exchange, and coordinated operation between upstream reservoirs and estuarine barrages.

The proposed ecohydraulic framework provides a scientific basis for sustaina-

ble management of coastal salinity-control structures under climate change, sea-level rise, and increasing freshwater demand pressures. The methodology can also be extended to other tropical estuarine and lagoon systems across Vietnam and Southeast Asia.

Acknowledgments

This article uses some information, data, and research results from the National Science and Technology Project “Research on evaluating the effectiveness of river damming projects in the Central coastal region on socio-economic and ecological environment”, project code ĐTĐL.CN-48/22, under the Basic Science Development Program in Chemistry, Life Sciences, Earth Sciences, and Marine Sciences for the period 2017-2025.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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