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Environmental impacts on water quality due to structural measures: A case study in Hung My commune, Chau Thanh district, Tra Vinh Province, Viet Nam

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ABSTRACT

Saltwater intrusion in the Vietnamese Mekong Delta has been significantly aggravated by both human development and adverse climate change. To curb salinization, local authorities rely heavily on structural measures (dikes, sluice gates, reservoir canals), yet their long-term environmental trade-offs remain underexplored. This study examines such environmental impacts and prioritization of measures in Tra Vinh province, Viet Nam. The research process combined field sampling of key water quality indicators at 25 sites, principal component analysis (PCA) to distil the main drivers, and in-depth interviews with ten risk-management experts. The findings reveal a potentially critical trade-off: measures provide operational benefits in reducing immediate intrusion, but this comes at the cost of elevated pollutant concentration and long-term degradation. This is evidenced by severe ecological stress, with many samples exceeding safe thresholds for DO, ORP, and TDS. Furthermore, the analysis confirmed strong interdependencies among conductivity, salinity, and total dissolved solids (correlation > 0.97). These results indicate the need for additional research on the ecosystem impacts of physical defenses, as well as consideration of non-structural approaches, including policy innovation, community engagement, and adaptive governance to support sustainable risk management against SI.

1. INTRODUCTION

The Vietnamese Mekong Delta (VMD) is in the southwest of the country which is one of the largest and most fertile plains in Southeast Asia (Hashimoto, 2001; National Agency for Science and Technology Information [NASATI], 2016). The VMD which consists of over 47% of the national cereal crop planted area (National Statistics Office, [NSO], 2024a) has always been the regional economic pillar with approximately 18 %÷20% countrywide Gross Domestic Product contribution (Piesse, 2019). Home to approximately 17.55 million people (NSO, 2024b), this tributary not only provides 50 per cent of the state's food supply but also plays a key role in agricultural exports in Viet Nam (International Federation of Red Cross and Red Crescent Societies [IFRC], 2020). As climate change has become more severe in the past decades (Sutton et al., 2019; World Meteorological Organization, 2023), VMD will be threatened by several natural adversities from coastal erosion, subsidence, period flooding, and saline intrusion (SI) (Nguyen, 2017; Nguyen et al., 2024). Amongst them, SI, a natural occurrence that results from rising sea levels, water use patterns, and drought, has significantly affected the vulnerability of communities across the region and threatening nationwide food security (United Nations Development Programme [UNDP] Viet Nam, 2016;

Nguyen et al., 2023). In particular, the period 2016 – 2020 witnessed the most relentless impact in the estuary's 90-year history (To et al., 2016; Nguyen, 2017; Eslami, 2022). In the 2016 drought, nine provinces and one municipality in VMD suffered economic losses of around 7,517 billion VND, with more than 284,000 hectares of rice and aquaculture areas heavily affected by extreme drought and SI (World Bank, 2017). In 2020, 685,558 individuals, of whom 130 thousand were children, were exposed to health risk conditions such as a lack of safe drinking water and poor hygiene (IFRC, 2020).

Approximately 2 million hectares of agricultural land are prone to the risks of salinity gradient (To et al., 2016), substantially reducing farming productivity regarding the crops, and aquaculture animals were known to have low tolerance to salt (Smajgl et al., 2015; World Bank, 2017). This trend, however, is unlikely to subside, as sea levels are expected to rise in the future (To, 2014). Consequently, SI would be estimated to invade deeper into the VMD's interior. According to Figure 1, the 4 g/*l* salinity intrusion boundary is projected to extend further upstream, reaching from 2 to 8 km by 2030 (baseline of the simulation) and expanding broadly from 7 to 18 km inland by 2050 (Ministry of Agriculture and Rural Development [MARD], 2016).

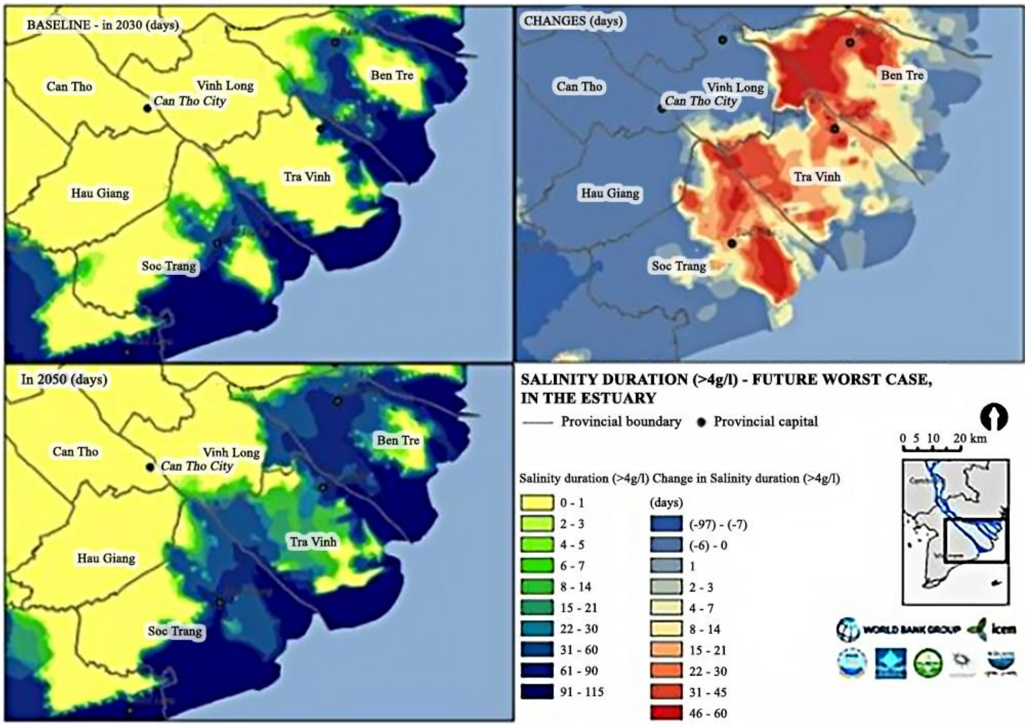

Figure 1. Changes in salinity duration (>4g/l) under the future worst-case scenario in the delta estuary

(Source: MARD, 2016)

Currently, state-of-the-art salt intrusion management practices are dominated by technical or structural measures (SM), primarily focused on preventing salinization and storing freshwater (MARD, 2016; NASATI, 2016; Nguyen, 2019). This approach involves investing in protective hydraulic infrastructure such as dikes, walls, dams, and sluice gates, which has become the primary method for controlling SI due to its short-term benefits (Nguyen, 2019). However, relying solely on SM poses significant long-term risks. In the context of the VMD, these methods have revealed several limitations and concerns. The use of structural interventions such as sluice gates and irrigation canals, although intended to enhance water management, is often associated with significant environmental and public health externalities. The management and operation of these systems substantially modify local hydrology, potentially resulting in challenges including waterlogging, soil erosion, and elevated soil and water salinization (Giordano et al., 2023). Additionally, the formation of stagnant or slow-moving water within canals and reservoirs can create optimal conditions for disease vectors, particularly Anopheles mosquitoes, thereby increasing the incidence of malaria and other water-related diseases in adjacent communities (Amerasinghe & Boelee, 2004). These effects disrupt local ecosystems, reduce biodiversity, and pose direct risks to human health, underscoring the importance of thoroughly appraising the environmental trade-offs inherent in such infrastructure projects. For instance, while sluice gates facilitate the storage and use of fresh water for crop irrigation during dry seasons or water shortages, they provide only a temporary solution, as the required water volume may be insufficient (World Bank, 2012). Moreover, unsustainable groundwater consumption can lead to increased salinity in remaining groundwater resources (World Bank, 2012; MARD, 2016). Additionally, economic conflicts between rice farming and shrimp aquaculture, exacerbated by poor water resource management, have resulted in indecisive land-use planning. Consequently, SI has re-emerged in previously desalinated zones, causing further financial losses and developmental setbacks (Tran et al., 2021). On the one hand, technical measures such as emergency pump stations and sluice gates have effectively reduced the presence of SI in agricultural fields (Nguyen, 2019; Viet Nam Government Portal, 2021). On the other hand, this approach may have aggravated the ecological impact on surface water quality, a concern that has not been extensively studied (Tuong et al., 2003; MARD, 2016). These issues are likely to place additional strain on the VMD's already vulnerable ecosystem. Risk Management (RM) is understood as a decision-making process aimed at reducing the consequences of an event. This process operates under uncertainty and involves implementing risk management plans, strategies, and measures (Schanze, 2006). RM is presented as an ongoing process of analysis and assessment to mitigate risk consequences (Hall et al., 2003). Specifically, disaster RM is defined as a process of gathering information, assessing options, suggesting courses of action, and making decisions to minimize risks (Phuong et al., 2020). While certain practices have shown positive results in SI risk management, some studies indicate that the same approaches may not be universally applicable. In the context of disaster RM, there remains a need to observe and endorse appropriate measures that address specific responses in particular regions, such as VMD.

Thus, this research broadens its focus to examine potential hazards associated with contemporary sustainable management issues, thereby thoroughly addressing this knowledge gap. This review includes empirical data from fieldwork, comprehensive interviews, and an analysis of currently available sustainable practices. The publication ultimately recognizes the research approach's limitations and emphasizes the need for more research in this spectrum.

2. METHODOLOGY

2.1. Conceptual framework

While structural measures such as dikes, sluice gates, and pump stations have received substantial investment in the Vietnamese Mekong Delta for decades, their long-term environmental trade-offs, particularly regarding canal hydrochemistry and aquatic health, remain underexplored. Existing research primarily highlights the short-term benefits of these measures in preventing salinization; however, a critical knowledge gap persists in linking the specific operational protocols of sluice gates to their downstream consequences, such as oxygen depletion, the accumulation of dissolved solids, and the subsequent impacts on the livelihoods of rice-farming communities. To address this gap, the present study integrates dry-season field sampling and Principal Component Analysis with in-depth expert interviews to assess the biochemical changes resulting from sluice gate closures and to understand the institutional rationale driving their continued use (Figure 2). Guided by this integrated framework, two central research questions are proposed:

1. How do current structural measures, especially sluice gate operations, affect the biochemical quality of irrigation water?

2. Which policy, legal, and management incentives favor sluice gates over non-structural approaches?

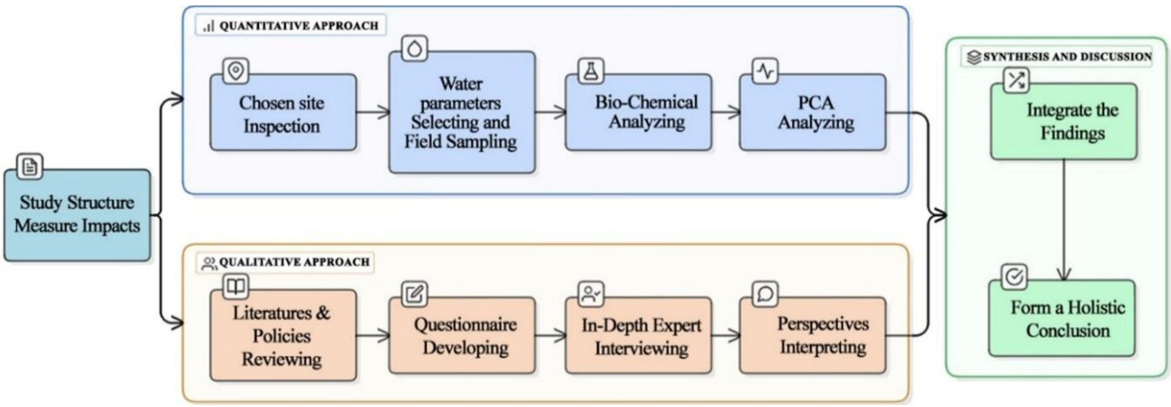

Figure 2. Overview of the research process

2.2. Studied area

2.2.1. Hung My commune, Chau Thanh district, Tra Vinh Province

Tra Vinh province (before the 2025 administrative merger) is characterized by a lower terrain, situated downstream of the Mekong River. The land is knowingly flat and thoroughly divided by both natural and artificial waterways, with an average elevation ranging from 0.6 meters to 1.0 meters (consisting of two-thirds total area) (Phuong et al., 2020). Furthermore, this area is vulnerable to sea-level rise under the medium-range emission scenario in 2030, when sea level could rise by 13 cm (Thuc et al., 2016). The research was conducted in Hung My commune, which is situated alongside the Co Chien River in the Chau Thanh District. The commune has a total land area of 28.29 square kilometers (2,829 hectares), of which 59 percent is designated as agricultural or forestry land (Hung My People's Committee, 2020).

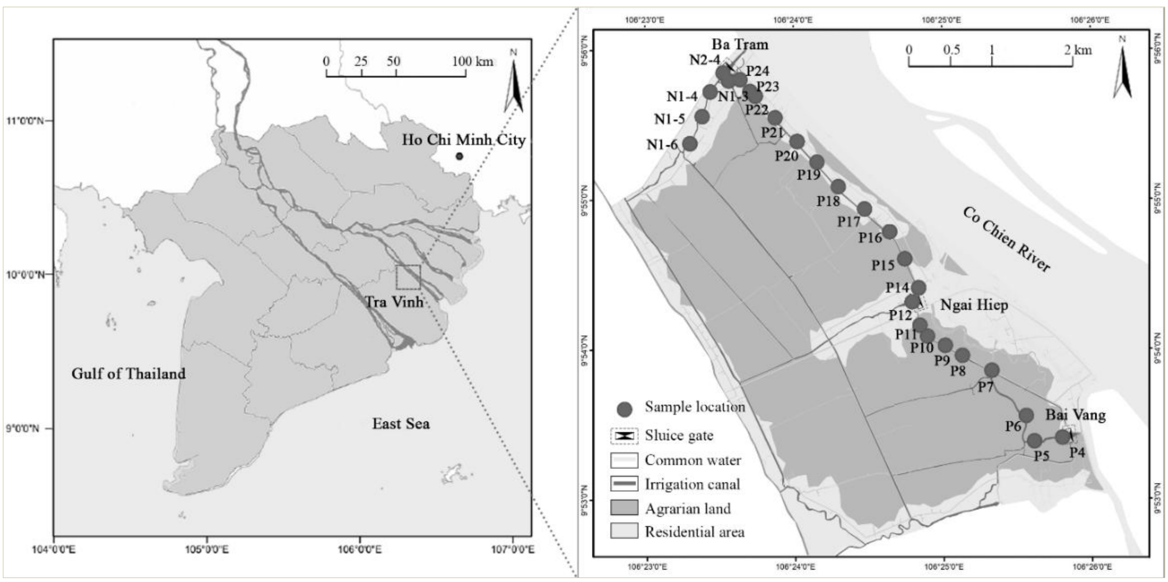

Figure 3. Sample's map in Hung My commune

(source by authors, 2023)

2.2.2. Water stress: Sluice gate system as a protection measure against saline invasion

The agrarian activities and domestic water consumption of Hung-My commune, which encompasses eight hamlets, are conducted through an irrigation channel network that draws fresh water directly from the Co Chien River. The technical approach, which involves the use of three manually operated sluice gates, has been implemented to retain freshwater in the channel. Three sluice gates serve as structural protection in the area: Ba Tram, Ngai Hiep, and Bai Vang Gate (figure 3). SI management of the sluice gates was based on real-time decisions from the local monitoring station, and no water exchange occurred if SI occurred. This helps limit the high salinity levels in the river water entering the irrigation canals and regulate the flow in the irrigation network. At the same time, sluice management aims to safeguard water sufficiency for agricultural activities. These gates, however, remain shut during the dry season to prevent SI when the salinity level exceeds the acceptable level.

2.3. Data collection and research methods

2.3.1. Water quality indicator analysis

Understanding the changes in saltwater intrusion in Tra Vinh Province, driven by both technical interventions and climatic variations, is crucial for mitigating their negative impacts. Primary data analysis in the study areas and expert interview investigation are the two typical methods to evaluate changes in the water quality of irrigation canals due to the intervention of technical measures and the popularity of structural measures employed in the VMD. Water quality indicator analysis is the first method for assessing changes in water quality resulting from sluice operations and other ongoing environmental challenges. Figure 3 displays the locations of 25 sampling sites in Hung My commune's irrigation network and nearby natural channels. Two coding schemes were used: P-sites (P4–P24), representing 20 sequential primary canal points from upstream (Ngai Hiep sluice gate) to downstream (Bai Vang sluice gate), and five N-sites (N1-3, N1-4, N1-5, N1-6, N2-4), marking reference points in secondary waterways near these gates. All positions were sampled once in May 2023, during peak dry season, to capture water quality under maximum salinity intrusion.

Although “single sampling” is a limitation, it was purposefully chosen to evaluate the irrigation system under peak environmental stress. Sampling during the height of the dry season targeted the most severe water scarcity and saltwater intrusion. Research supports this method, showing that water quality in stagnant or low-flow systems stabilizes after initial changes; for instance, bacterial counts remain stable in buildings with prolonged low water usage (Kim et al., 2023). In those systems, flushing provided only temporary improvements, with water quality returning to pre-flush levels within one week. Similarly, in residence halls that were not intentionally flushed, key water quality indicators did not differ significantly between two sampling events held three weeks apart (Greenwald et al., 2022). This evidence suggests that once the water in a closed system reaches a stable state, its quality tends to remain stable over time. This means that taking a single sample at the right moment can reliably reflect the typical, worst-case water conditions in the system.

Utilizing the water quality indicators presented in Tables 1 and 2, research data were systematically gathered from those designated sampling points along the irrigation system.

TDS refers to the quantity of dissolved or soluble substances in water, often measured in milligrams per litter (mg/L). The survival, growth, and reproduction of aquatic species are significantly influenced by the concentration of dispersed ions in water. The cool’s tail (Ceratophyllum Demersum) and cattails (Typha sp.) aquatic plants, which are very common in all continents except Antarctica, are nearly eliminated when the suspended solid particles increase from 270 to 1170 mg/L (Masters & Wendell, 2013). This element was shown to expressively affect the grass embryo during the water-hardening phase immediately following fertilisation (James, 2023). TDS should be consistently managed to provide a water-quality environment conducive to organism reproduction.

Table 1. Water quality indicators, their abbreviations and units

Surface water indicators	Abbreviation	Unit
Hydrogen-ion concentration	pH	pH units
Oxygen reduction potential	ORP	mV
Dissolved Oxygen	DO	% - mg/L
Electrical conductivity	EC	µS/cm
Total dissolved solids	TDS	mg/L
Salinity	S	PSU
Total Nitrogen	TN	mg/L
Total Phosphorus	TP	mg/L

Table 2. Overview of water quality indicators: definitions, thresholds, units, and references

Name	Descriptions	Ranges	References
TDS	Measures the total concentration of dissolved ions (e.g., Na^+, Cl^-, Ca^{2+}), reflecting water hardness and potential toxicity to biota.	<500 mg/L (optimal for aquatic life); < 1000 mg/L (freshwater category); 500–3750 mg/L (tolerable); > 3750 mg/L (fatal)	Bozorg-Haddad et al. (2021); DataStream (2021); Ayers & Westcot (1994)
DO	Indicates the amount of oxygen available for respiration by fish and invertebrates; low DO signals organic pollution or stagnation.	≥ 6.58 mg/L (healthy); ≥ 4 mg/L (Vietnamese standard); < 3 mg/L (fatal for fish)	Wetzel & Likens (2000); MONRE (2023)
ORP	Reflects the redox status of water, indicating its capacity to oxidize organic matter and self-purification; lower values imply reducing conditions.	300–500 mV (optimal); < 300 mV (insufficient oxidation capacity)	DataStream (2021); Weber-Scannell & Lawrence (2007)
EC	Quantifies the ability of water to conduct electricity, which is directly correlated with dissolved ionic content and salinity levels.	< 700 µS/cm (no restriction); 700–2300 µS/cm (moderate restriction); > 3000 µS/cm (severe restriction)	Ayers & Westcot (1994)
Salinity	Measures the concentration of dissolved salts (primarily NaCl), determining suitability for aquatic species and irrigation use.	< 0.5 PSU (freshwater); 0.5–3.0 PSU (irrigation safe); > 3.0 PSU (unsafe)	DataStream (2021); Ayers & Westcot (1994)
TN	Sum of all nitrogen compounds, including organic nitrogen and ammonia.	≤ 0.6 mg/L or 1.5 mg/L	QCVN 08:2023/BTNMT surface water A or B
TP	Indicates the combined concentration of dissolved and particulate phosphorus in water.	≤ 0.1 mg/L or 0.3 mg/L	QCVN 08:2023/BTNMT surface water A or B

Measuring dissolved oxygen (DO) is crucial for assessing aquatic conditions (Novotny, 2002). Most aquatic life, such as fish, cannot survive if DO falls below 5 mg/L. Low or absent DO indicates contamination and plays a key role in evaluating water quality, managing pollution, and guiding treatment processes (Brix et al., 2010).

ORP indicates a water body's ability to self-purify by breaking down waste and pollutants, largely depending on dissolved oxygen and similar substances. A drop in ORP reduces dissolved oxygen, increases contaminant toxicity, and hinders decomposition of organic material. High pH means reducing agents and results in negative ORP values. Overall, ORP helps understand aquatic chemical dynamics and guides decisions for better water quality management.

Significant changes in EC may be due to either natural tidal activities, evaporation, or artificial contamination and can be very harmful to water quality. Therefore, an abrupt fluctuation in conductivity in a water body may indicate the risk of contamination.

For nutrient concentration indicators, the ecological threshold for total nitrogen has been identified as 1.80 mg/L based on Threshold Indicator Taxa Analysis (TITAN). The threshold for total phosphorus is set at 0.039 mg/L using the frequency distribution method (Wu et al., 2022). Additionally, in 2015, the U.S. Environmental Protection Agency (EPA) established recommended nutrient criteria for various ecoregions, typically ranging from 0.5–1.0 mg/L for total nitrogen (TN) and 0.02–0.10 mg/L for total phosphorus (TP). Elevated levels of nitrogen, often originating from anthropogenic sources, can result in the over-enrichment of aquatic systems, a phenomenon referred to as eutrophication. Phosphorus also serves a crucial role in aquatic ecosystems; in many freshwater environments, it functions as the limiting nutrient, thereby regulating phytoplankton growth. Consequently, even marginal increases in total phosphorus can stimulate rapid algal proliferation, potentially leading to severe eutrophication. These processes may contribute to water quality degradation and biodiversity loss. Additionally, the Vietnamese standard for surface water (QCVN 08:2023/BTNMT) was included in the comparison to provide context for the analysis. The two selected criteria are "Level A: Excellent Water Quality," indicating suitability for domestic supply, and "Level B: Moderate Water Quality," indicating suitability for industrial production and agriculture after appropriate treatment.

2.3.2. Principal component analysis (PCA)

Principal Component Analysis (PCA) was used to identify dominant factors affecting surface water quality and to reduce the complexity of the multivariate dataset from 25 sampling sites. This dimensionality reduction technique transforms correlated water quality parameters into a set of uncorrelated principal components (PCs) that retain the maximum possible variance.

This method involves several steps: (1) standardizing variables, (2) computing the covariance matrix, (3) performing eigenvalue decomposition to determine variance direction and magnitude, (4) selecting principal components based on eigenvalue ranking, (5) projecting data onto the reduced PC space, (6) using a scree plot to visualize eigenvalue distribution, and (7) assessing cumulative explained variance.

By implementing these steps, PCA simplifies interpretation by highlighting the most informative indicators, enabling more effective spatial clustering and inter-parameter correlation analysis of water quality dynamics in the study area.

2.3.3. Expert in-depth interview

To examine the rationale behind existing risk management policies, in-depth interviews were conducted with 10 experts (Figure 4). These interviews included individuals with backgrounds in research, policymaking, and planning (see Table 3) to address two key questions related to saline intrusion risk management.

i) "*What are the current approaches towards saline intrusion risk management in from the government policy theme?* "

ii) "*The combination of structural and non-structural measures is the standard choice in risk management to deal with the increasing saline damage trend. Should the next phase of saline intrusion risk management strategy be steered to non-structural measures application?*

Figure 4. An expert in-depth interview session at the Tra Vinh DRM office

(photo by authors,2023)

Table 3. List of experts and their respective fields

	Interviewee Profile(s)
1	Researcher working in the field of Water Management and Climate Change.
2	Spatial planner working for local planning authorities.
3	Researcher working in the field of Environment & Natural Resources.
4	Urban planner working for a local company. Freelance Journalist of urban planning.
5	Researcher working in the field of Water Management and Climate Change.
6	Researcher working in the field of Water Management. Founder of the Climate Change Coordination Office of local authorities.
7	Researcher working in the field of Water Management. Officer of the Viet Nam Academy for Water Resources (VAWR) and Member of the Viet Nam Panel on Climate Change (VPCC).
8	Researcher working in the field of Water Management and Climate Change.
9	Researcher working in the field of Environment & Natural Resources.
10	Researcher working in the field of Water Management and Climate Change. An officer working for the Department of Science and Technology of the local authorities.

In response to the first question, experts identified current strategies as a blend of regulatory frameworks, infrastructure development, and community-based interventions, which are often prioritized because they represent short-term fixes that provide a rapid response to critical events. As a result, there was strong governmental emphasis on physical barriers for coastal protection, supplemented by land-use planning guidelines and public awareness campaigns. However, these efforts frequently lack integration and a long-term vision, resulting in fragmented regional responses.

Regarding the second theme, interviewees agreed that non-structural measures must take precedence in Viet Nam's next phase of risk management. While combining structural and non-structural approaches is standard, they advocated shifting focus to adaptive solutions such as improved water management, sustainable land-use practices, and community engagement. They recommended leveraging modern technologies, integrating policies, and deepening stakeholder involvement to effectively complement existing infrastructure.

3. FINDINGS

3.1. Water quality observations

3.1.1. Environmental impacts from the stagnating water quality indicators

A total of 25 samples were collected within the channels (Figure 3), as depicted in the accompanying map and illustrated in the charts presented in the results section. In addition, Nutrient Exceedance samples were collected from the sites. All data was collected and measured by the designated research staff. The condition of the standing water in the channel remained unchanged, thereby justifying the decision to proceed with a one-time sampling effort. This approach was approved by the staff based on findings from a pilot survey conducted two days prior, during which five samples were collected from five distinct locations. The pilot survey confirmed the stability of the water conditions, supporting the conclusion that a single round of sampling was sufficient. The findings from the examination of several physicochemical parameters are shown in the following illustrations.

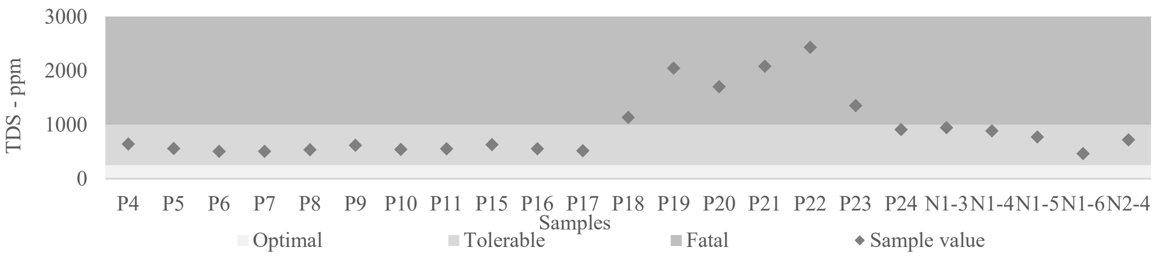

Figure 5. Variation of TDS collected in May 2023

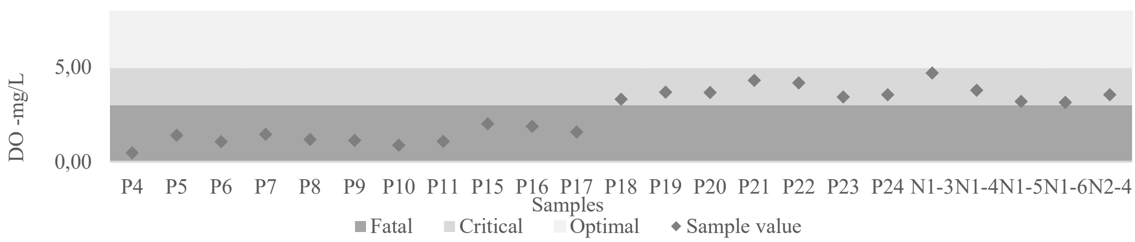

Figure 6. Variation of DO collected in May 2023

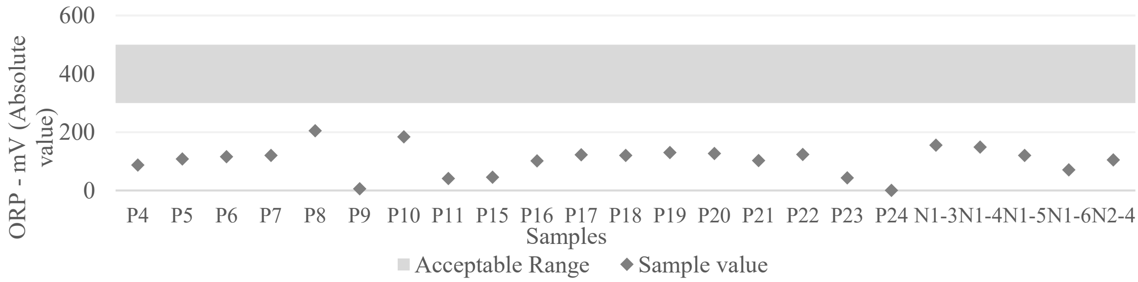

Figure 7. Variations of Oxygen Reduction Potential collected in May 2023

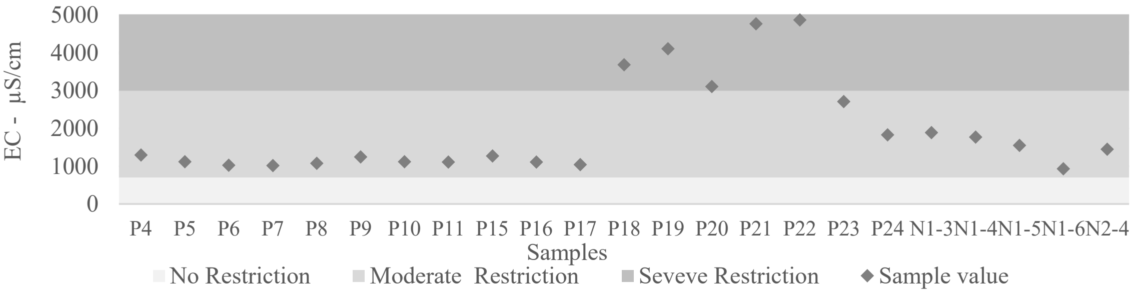

Figure 8. Variations of Electrical Conductivity collected in May 2023

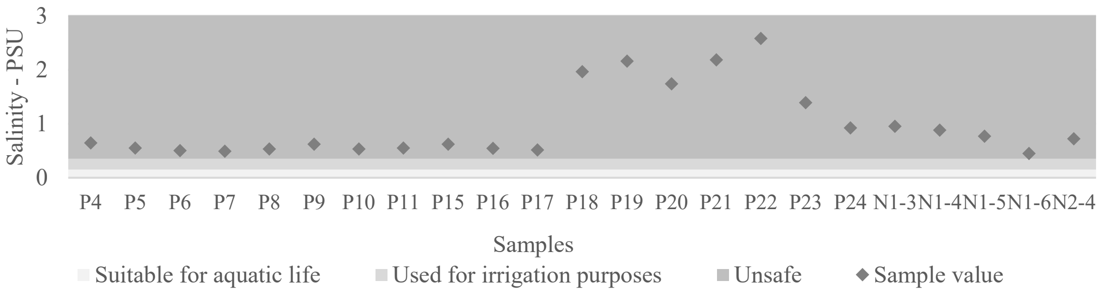

Figure 9. Variations of salinity value collected in May 2023

Table 4. Comparison of nutrient concentrations against regulatory and ecological thresholds

Parameter	**Unit**	**Sample range** (lowest to highest)	**QCVN 08** surface water B	**QCVN 08** surface water A	**United States Environmental Protection Agency (2015)** Suggestions for streams and rivers	**Ecological threshold** (Wu et al., 2022)
Total N	mg/L	from **0.276** to **0.416**	≤ 1.5	≤ 0.6	0.5 - 1.0	0.18
Total P	mg/L	from **0.565** to **0.832**	≤ 0.3	≤ 0.1	0.02 - 0.10	0.039

Results from May 2023 indicate a hydro chemical disturbance in the irrigation network. All sampling sites showed total dissolved solids exceeding typical freshwater levels, reaching up to 2,437 mg/L, and half of the locations recorded dissolved oxygen concentrations below the 4 mg/L threshold. Redox potential values were consistently below 300 mV, suggesting limited self-purification capacity. Conductivity and salinity increased at downstream sites, corresponding to ion accumulation in semi-enclosed pools formed by manually operated sluice-gate closures. During periods when gates remain closed in the dry season, water column reaeration decreases, while higher temperatures and evaporation increase salt concentration, which may exacerbate stagnation and chemical changes.

Nutrient measurements further inform this assessment. Total phosphorus levels ranged from 0.565 to 0.832 mg/L, exceeding the Vietnamese QCVN 08:2023 and ecological thresholds, indicating conditions conducive to eutrophication and algal blooms. Total nitrogen values (0.276–0.416 mg/L) met national and U.S. EPA standards but exceeded the ecological benchmark of 0.18 mg/L, potentially affecting ecosystem processes. These nutrient distributions may have implications for biodiversity, oxygen dynamics, and the resilience of the canal system.

Table 5 shows that DO concentrations in Hung My (0.47–4.70 mg/L) were generally lower than those reported in other Mekong Delta waterways. The recorded TDS values (466–2,437 mg/L) overlap with broader regional observations, though they extend below the 540 mg/L minimum threshold previously reported by Nguyen et al. (2018). This comparison indicates considerable spatial variability across Mekong Delta canal and river systems and provides regional context for subsequent causal analysis.

Table 5. DO and TDS comparison: This study vs. other VMD research

Study	Location (Canal/Reach)	DO (mg/L)	TDS (mg/L)
This study (May 2023)	Hung My irrigation canals	0.47 - 4.70	466 - 2,437
Nguyen et al. (2018)	Tien River riparian waterways	N/A	540 - 5,670
Mutea et al. (2021)	Hau River, An Giang - Can Tho	3.7 - 5.7	N/A
Le et al. (2023)	Tra Vinh canal-river network	3.0 - 5.8	N/A
Nguyen & Nguyen (2023)	Soc Trang coastal rivers and canals	2.68 - 3.6	N/A

N/A = parameter not reported in the cited study

3.1.2. PCA analysis of water quality observations

The observation map (Figure 10) illustrates the clustering of sampling points based on similar water-quality concentrations. The data revealed that samples were categorized into the following groups according to dimension 1 (λ = 113.349, τ = 64%) and dimension 2 (λ = 33.732, τ = 19%) (Figure 11):

Group 1: P18, P19, P20, P21, P22, P23, P24 (7 samples).

Group 2: P8, P9, P10, P11 (4 samples).

Group 3: P4, P5, P6, P7, P15, P16, P17 (7 samples).
Group 4: N1-3, N1-4, N2-4, N1-5, N1-6 (5 samples).

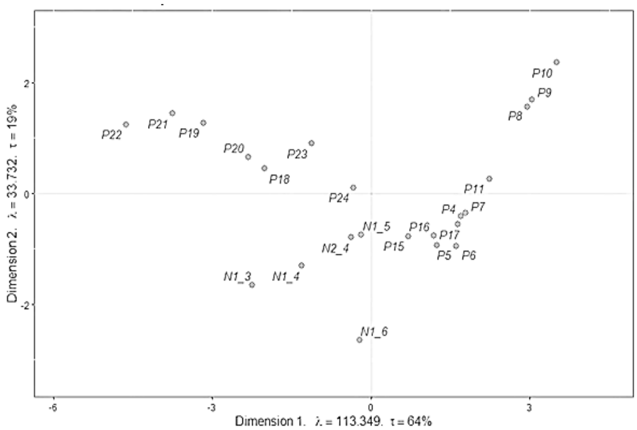

Figure 10. Observation Map of the water quality of the collected samples

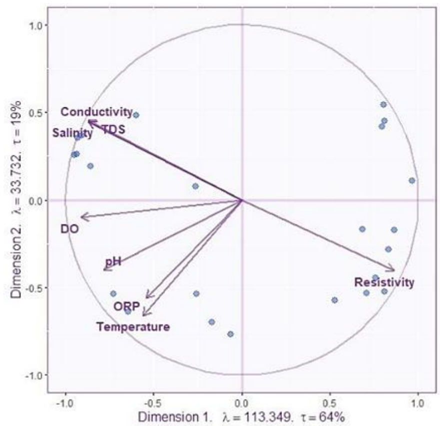

Figure 11. Principal Component Analysis (PCA) of the water quality of the collected samples

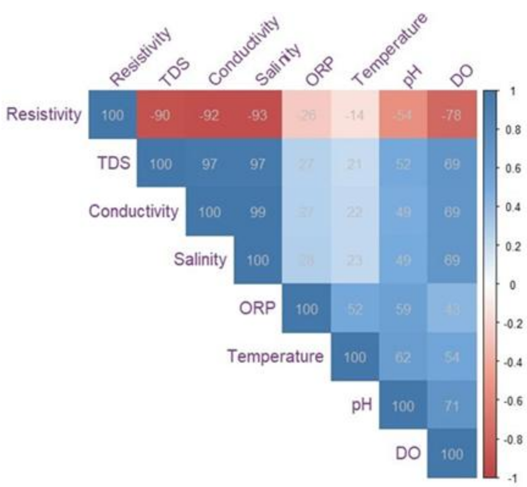

Figure 12. Correlation heat map of water quality parameters in Hung My Commune

The results of the correlation analysis reveal that total dissolved solids, conductivity, and salinity in surface water samples are negatively correlated with resistivity, displaying correlation coefficients of -0.90, -0.92, and -0.93, respectively. In contrast, there is a strong positive relationship between conductivity and salinity, as indicated by a correlation coefficient of 0.97. Notably, the most robust association is between conductivity and salinity, with a correlation coefficient of 0.99 (see Figure 12).

The "grouping samples" step refers to visualising and interpreting how samples cluster together based on their similarity in the reduced-dimensional space created by PCA. As shown in Figure 10, these samples were categorized into groups according to dimension 1 and dimension 2 (as a pre-processing step for clustering by projecting high-dimensional data onto a lower-dimensional space defined by the principal components). So, the relationship of these groups is to visualize the tendency of data according to dimension 1 (λ = 113.349, τ = 64%) and dimension 2 (λ = 33.732, τ = 19%). PC1 (salt-stagnation axis), which explains 64 % of the dataset's variance, is driven by high loadings on salinity, conductivity, and TDS and thus represents the salt-accumulation/stagnation gradient; PC2 ("aeration-redox axis," 19 % of variance) is dominated by dissolved oxygen and ORP, marking the canal's aeration status.

3.2. Linking structural measures to water-quality degradation

The severe decline in water quality under sluice gate operations provides the basis for the causal pathway analysis in this section. The observed hydro-chemical shifts, specifically the elevated ion concentrations and reduced dissolved-oxygen levels, are strongly validated by the Principal Component Analysis (Section 3.1.2, Figure 11). PC1, which accounts for 64% of the variance, is strongly influenced by salinity, conductivity, and TDS, capturing the distinct stress signature of downstream water under closed-gate conditions. In contrast, PC2 (19% variance) is driven by dissolved oxygen and ORP, reflecting the better-aerated upstream state. This statistical concordance demonstrates that manual sluice gate closures directly sculpt the canal's chemical fingerprint, reinforcing the causal chain from infrastructure operation to oxygen depletion and ion accumulation. This dependence on physical measure means that during peak salinity periods, managers shut the gates, which cuts off the natural exchange of water between canals and the river. This creates stagnant, semi-enclosed pools of water with very little flow. The field data from May 2023 confirms that this stagnation dramatically reduces the water's ability to re-oxygenate, leading to lower dissolved oxygen and redox potential (Figures 6 and 7), while dissolved salts and other ions become more concentrated, as seen in the higher conductivity, TDS, and salinity levels downstream (Figures 5 and 8). These shifts in hydrology and chemistry set the stage for an ecological imbalance that threatens the health of the irrigation network and, ironically, undermines the goal of storing fresh water for rice farming.

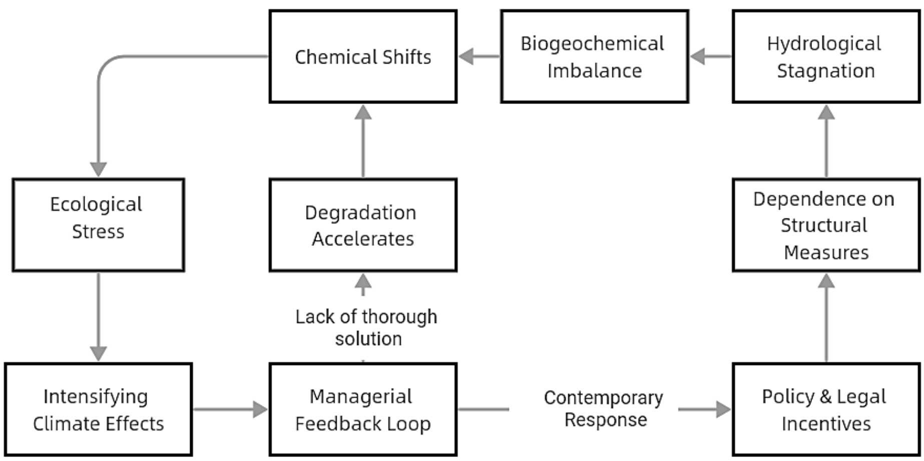

Figure 13. The causal chain linking regulatory incentives, sluice gate operations, and ecological degradation in the study site's irrigation system

These chemical changes put immense stress on both the aquatic environment and local agriculture. Salinity and total dissolved solids often climb past levels that freshwater organisms can tolerate, while dissolved oxygen drops to near-fatal lows for fish and invertebrates. For local farming families who rely on this water for their rice paddies, the poor quality means weaker crops, smaller harvests, and higher costs associated with trying to find alternative water sources or flushing the salt from their soil. Despite these clear signs of environmental and economic damage, the typical response from managers is to keep the gates closed to block saltwater, a short-term fix that overlooks the long-term harm. This problem is made worse by climate change, as hotter, longer dry seasons accelerate evaporation and further concentrate salts, locking the system into a self-reinforcing cycle of stagnation and decay. Figure 13 illustrates this entire causal chain, from policy to ecological impact. It also helps pinpoint key opportunities for intervention. Adaptive governance, community-based monitoring, and new operational rules for the sluice gates could help balance saltwater protection with the need for good water quality, a healthy ecosystem, and the economic survival of Tra Vinh's rice-farming communities.

Several interviewees remarked that sluice gate closures are considered the only expedient tool for managers under political pressure for quick results. The operation of these gates creates the semi-enclosed, low-flow conditions documented in this study, resulting in dissolved oxygen falling below 4 mg/L at half of the sites and salinity rising to unsafe levels. This finding establishes a direct link, demonstrating how managerial priorities translate into the severe water-quality degradation observed.

4. LIMITATIONS

The study, by contrast, has several shortcomings that must be acknowledged. Among these weaknesses are the constrained scope, the insufficient data collection procedure, and the inadequate environmental evaluation.

Foremost, the study focused specifically on Hung My commune within the Tra Vinh province which is a geographic restriction. Hence, the findings and observations might not be representative of other areas within the VMD with different hydrological conditions, land-use patterns, and salinity intrusion levels. Expanding the research to include multiple case studies across the delta with varying environmental conditions, socio-economic contexts, and management approaches would provide a more robust understanding of the setting. The temporal element is also neglected as water quality can vary significantly throughout the year due to seasonal changes in precipitation, hydrological volume, and tidal patterns (Chen & Orton, 2023). The study's findings are derived from water quality data collected in May 2023. However, long-term monitoring of water quality and other environmental parameters is essential for evaluating the effectiveness of SI risk management strategies and for identifying any unintended consequences or delayed impacts that may arise over time (Beak et al., 2024). Therefore, a more comprehensive study would broaden information collection over multiple seasons to fully capture all data iterations.

Regarding the investigation procedure, the study primarily relied on a single sampling event to assess water quality. As a result, there are disregarding to dynamic nature of the local water source which can fluctuate due to various external factors i.e. climate and anthropogenic (Liu et al., 2017). While the study included 25 sampling points, spatial coverage may not be sufficient to capture the full extent of water quality variations within the commune, especially in areas with diverse land use and hydrological conditions. Increasing the number of sampling points and strategically locating them based on land use, water flow patterns, and proximity to sluice gates would enhance the spatial representation of the data. In the same vein, the interviewees were selected for their expertise and involvement in SI risk management, the small sample size may limit the diversity of perspectives and experiences captured. The current assessment parameters also lack variety as other important factors, such as nutrient levels (nitrogen, phosphorus), heavy metals, and pesticide residues, were not included in the analysis (Beak et al., 2024). Other environmental aspects, such as biodiversity loss, habitat degradation, and soil salinization, also need to be investigated to understand the full extent of any drawbacks structural measures may cause. These excluded parameters could provide a more comprehensive understanding of the environmental impacts of SI and sluice gate operations.

5. CONCLUSION

Based on the outlined conceptual framework, this mixed-methods study finds that closing sluice gates during the dry season leads to changes in canal hydrochemistry: dissolved oxygen decreases below certain thresholds, total dissolved solids and salinity increase above typical limits, and nutrient imbalances particularly higher phosphorus levels are observed with potential implications for aquatic life and paddy irrigation. Principal Component Analysis indicates strong associations among conductivity, salinity, and TDS, while semi-enclosed, low-flow conditions resulting from manual gate operations are identified as a main factor contributing to stagnation and water quality decline. Expert interviews indicate that structural approaches are commonly prioritised due to regulatory requirements, political factors, and the need for rapid salt exclusion, despite recognised ecological impacts over time. Addressing these trade-offs may involve incorporating adaptive governance, community monitoring, and non-structural strategies into local risk management policies to support both ecosystem health and rice-farming livelihoods in Hung My commune, Tra Vinh province.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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