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An assessment of water management to cope with saltwater intrusion: A case study of Chau Thanh district, Ben Tre province, Viet Nam

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ABSTRACT

Water security and agricultural productivity in the Vietnamese Mekong Delta are at risk due to several water-related issues, most notably saltwater intrusion. Using historical data from 2011–2018 at 21 monitoring stations, this study applied percentile-based spatial interpolation to map saltwater intrusion at the 1 percent, 10 percent, and 50 percent salinity percentiles. Results reveal that extreme events (1st percentile) affect 51% of the district's area with salinity >4 g/L, while typical years (50th percentile) affect 16% of the area, with eastern communes most vulnerable. The current irrigation system, comprising 13.2 km of canals, 79.4 km of embankments, and nine sluices, remains incomplete, thereby limiting control of saltwater intrusion. A planned network of 33 sluices by 2030 aims to enclose the system, supported by tailored water management strategies, including sluice operations, water transfer via the Ba Lai River, and storage of 12 million m³ in canals. These measures could ensure freshwater availability for orchards and domestic use. The study underscores the urgency of finalizing infrastructure and planning storage zones to address dry season shortages, offering insights for sustainable water management in the Vietnamese Mekong Delta under climate change pressures.

1. INTRODUCTION

The Vietnamese Mekong Delta (VMD) is a vital component of the nation's agricultural economy, providing more than half of its rice and sustaining the livelihoods of about 17 million people (Hanington et al., 2017). This vast delta, which spans about 40,000 square kilometers in southern Vietnam, is bounded by a complex system of rivers, canals, and estuaries that connect the East Sea to the Mekong River. However, because of its low-lying areas and proximity to the coast, it is highly vulnerable to saltwater intrusion, the inland movement of saline water into freshwater systems, which endangers ecosystem health, freshwater resources, and agricultural productivity (Thanh et al., 2020). Sea level rise associated with climate change, decreased upstream freshwater flows as a result of damming, and other factors have all contributed to the intensification of saltwater intrusion in recent decades, and overuse of groundwater for household and agricultural purposes (Smajgl et al., 2015). The significant temporal and spatial variability in salinity levels, driven by these pressures, has made it more difficult to effectively manage water resources and adapt to shifting environmental conditions.

Given the ecological and socioeconomic consequences, saltwater intrusion in the VMD has attracted considerable attention. van Aalst et al. (2023) revealed that salinity incursions are becoming more frequent and severe, especially during the dry season when river discharge is at its lowest. During the severe drought of 2015–2016, for example, saline water affected more than 250,000 hectares of rice, damaging and spread up to 90 kilometers inland (Thach et al., 2023). According to climate models, sea levels could rise by 26 to 106 cm by 2100, depending on scenarios for greenhouse gas emissions, which could worsen this trend (Ministry of Natural Resources and Environment, 2021). A decrease in sediment and freshwater delivery to the delta has resulted from upstream hydropower development along the Mekong River (Ang et al., 2024). This has increased saltwater intrusion (Dat et al., 2011; Kondolf et al., 2018). These interrelated challenges highlight the necessity of a reliable analysis to identify and map regional salinity patterns.

Spatial interpolation techniques have emerged as critical methods for estimating environmental variables such as salinity in areas with sparse data. Traditional approaches, such as inverse distance weighting (IDW) and kriging, have been widely applied to interpolate salinity in coastal regions (Li & Heap, 2014; Thanh et al., 2020). For example, Bui et al. (2024) mapped the VMD's salinity gradients using IDW, analyzing vulnerability of rice production to saline intrusion. However, by focusing on mean values and assuming a Gaussian distribution of data, these approaches may mask the extreme salinity levels that are most important for water management and agriculture. In contrast, percentile-based interpolation provides a more nuanced representation of risk zones and thresholds by highlighting the statistical distribution of salinity, such as the 1st, 10th, and 50th percentiles. Flood risk mapping has seen success with this approach (Merwade et al., 2008), but little is known about how it can be used to treat saltwater intrusion (Le et al., 2022).

This study aims to address these gaps by employing a percentile-based spatial interpolation approach to map saltwater intrusion across Chau Thanh district, Ben Tre province in the VMD. To this effort, we create high-resolution salinity maps that capture both average conditions and critical extremes by using field measurements and historical salinity data from hydrological monitoring stations. Then a spatial statistic was applied to compute potentially affected areas. Results present the spatial patterns of saltwater intrusion, evaluate how well percentile-based interpolation captures extreme salinity events, and support policymakers and local managers in water management. The foundation for a thorough analysis of implications for sustainable water management to cope with saline intrusion.

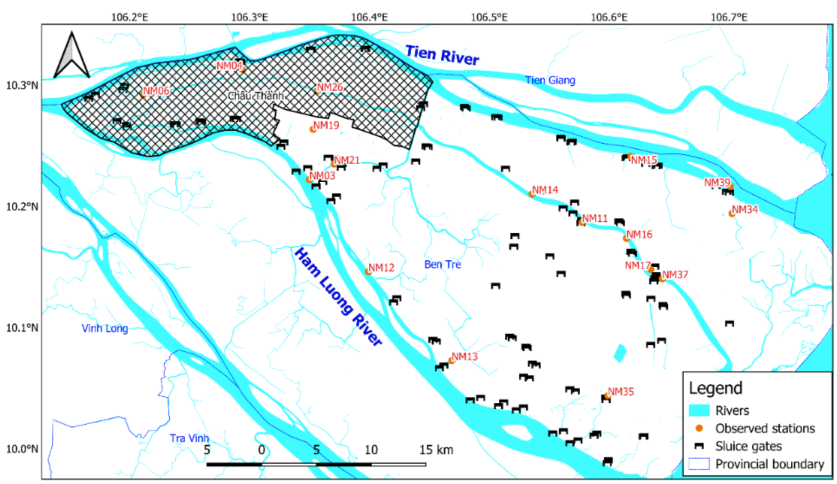

Figure 1. Locations of salinity monitoring stations

2. STUDY AREA

Chau Thanh district, located in Ben Tre province (before the 2025 administrative merger) within the VMD, spans approximately 22,489 hectares and is situated between the Ham Luong and Tien rivers, which are primary conduits for saltwater intrusion from the East Sea. The district's low-lying topography, with elevations averaging 1–2 meters above sea level, exacerbates vulnerability to salinity intrusion during the dry season (February–May).

The region supports a population of approximately 175,900 (in 2019), with agriculture, particularly fruit orchards, being the dominant economic activity (Veettil et al., 2019). Ben Tre province hosts 21 salinity monitoring stations along rivers and canals to capture spatial and temporal salinity variations (Figure 1). The hydraulic infrastructure is designed to mitigate saltwater intrusion but remains incomplete.

The hydrological system of Chau Thanh is influenced by tidal dynamics from the East Sea, and freshwater flows from the Mekong River via the Ham Luong and Tien rivers.

The canal network facilitates irrigation and drainage but is susceptible to salinity intrusion during low-flow periods. Tidal variations cause salinity fluctuations, with peaks observed in severe drought years (e.g., 2016, 2020) (Bui et al., 2025; Nghia et al., 2024; Tran et al., 2024).

Hydrological regimes in Ben Tre province are characterized by an extensive and intricate hydrological network critical to its agricultural and socio-economic systems. The province features a dense river system with a total length of approximately 6,000 km and a density of 2.5 km/km², encompassing four major rivers: My Tho (90 km), Co Chien (80 km), Ham Luong (70 km), and Ba Lai (55 km), alongside numerous smaller rivers, canals, and ditches. These waterways, interconnected across the province, serve as natural boundaries (e.g., the My Tho River between Ben Tre and Tien Giang provinces) and vital conduits for irrigation and transportation, discharging into the East Sea through multiple estuaries, including Cua Dai, Co Chien, Ham Luong, and Ba Lai. During the flood season, the Tien River supplies approximately 52% of the combined Tien and Hau river flows, with My Tho River carrying 6,480 m³/s (e.g., 3,360 m³/s via Cua Ham Luong) and Co Chien River 6,000 m³/s (e.g., 3,120 m³/s via Cung Hau). In the dry season (July to May), these flows decrease significantly to 1,598 m³/s for the My Tho River (e.g., 828 m³/s via Ham Luong) and 1,480 m³/s for the Co Chien River (e.g., 769.6 m³/s via Cung Hau), exacerbating saltwater intrusion challenges.

3. MATERIALS AND METHOD

3.1. Data collection

This study collected secondary data on locations and salinity at monitoring stations and hydraulic structures. These data were collected from the Ben Tre Department of Agriculture and Environment (formerly Ben Tre Department of Environment and Natural Resources) and the Hydrometeorological Center of Ben Tre province. Data on saltwater intrusion from 2011 to 2018, water resource management in the district, and possible solutions for managing and regulating water resources for agricultural irrigation purposes were obtained from the Chau Thanh Office of Agriculture and Environment (formerly Chau Thanh Office of Agriculture and Rural Development). Salinity data during the dry seasons along major rivers, canals, and estuaries were collected at 21 monitoring stations distributed across Ben Tre province (Figure 1).

3.2. Percentile-based spatial interpolation methods

We used a percentile-based spatial interpolation approach, which provides a statistical framework for capturing the variability and extremes of salinity levels at the monitoring stations, to map the spatial distribution of saltwater intrusion in Chau Thanh district. Percentile-based interpolation highlights the distributional features of the data, offering estimates at the 1st, 10th, and 50th percentiles. This is more beneficial for better water management compared to average conditions (Webster & Oliver, 2008). In the context of agricultural thresholds and water resource management, this study classified salinity levels of 0, 2, and 4 (g/L) based on the sensitivity levels of paddy rice crops (Nisa et al., 2022; Rad et al., 2011).

3.2.1. Frequency curve of salinity

The salinity frequency curve is developed through the following steps: (i) For each monitoring station, the highest salinity value recorded annually is defined; (ii) The salinity frequency curve is then constructed using the empirical formula (Equation 1), which is applicable to a single sample. Based on the annual maxima of salinity at each station, we used the FFC 2008 software (developed by the Thuyloi University) for frequency analysis and plotting to determine salinity concentrations corresponding to selected percentiles. The formula used is as follows:

$$P(X \geq X_0) = \frac{m}{n+1} \times 100 \quad (1)$$

where n is the number of observations, and m is the number of occurrences of the event X compared to that of X_0 in the input data.

From the generated frequency curve, salinity levels are determined for the selected frequencies of P=1%, P=10%, and P=50%. The salinity levels derived for the selected frequencies (P=1%, P=10%, and P=50%) are compared with the input time series. A representative year is selected based on salinity values that closely approximate those obtained from the frequency curve for each corresponding selected frequency.

3.2.2. *Spatial interpolation*

The selection of spatial interpolation methods depends on the characteristics of saltwater intrusion and the distribution of input samples. Figure 2 illustrates the longitudinal variation in salinity of the Co Chien - Cung Hau estuary on April 15, 1998. It indicates that salinity changes from the river mouth exhibit a relatively linear pattern. Based on salinity data and their distribution across stations in Ben Tre province, the linear interpolation method was chosen to generate salinity maps. This method produces a smooth surface, even with a limited number of input sample points, and employs a linear equation (Naoum & Tsanis, 2004) to calculate saltwater intrusion. Thus, the linear spatial interpolation was performed to estimate salinity across Chau Thanh, including land areas, assuming a correlation between surface and affected land areas due to the flat topography and extensive canal network. This interpretation is commonly used by (Khong et al., 2018; Thai et al., 2022; Thach et al., 2023).

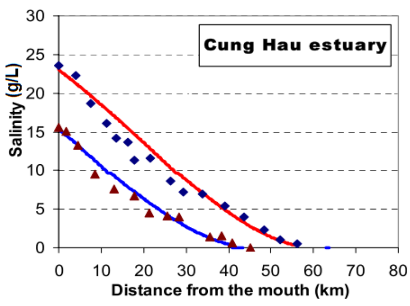

Figure 2. Distribution of saltwater intrusion into Cung Hau estuary on April 21, 2005, showing values of measured salinity at High Water Slack (diamonds), and Low Water Slack (triangles)

(Source: Nguyen et al., 2008)

3.2.3. *Cross-validation*

Cross-validation assessed prediction accuracy for salinity percentiles of 1%, 10%, and 50%. Leave-one-out cross-validation yielded Root Mean Square Error (RMSE) and Mean Absolute Error (MAE), shown in Table 1. The RMSE and MAE errors indicate the performance of the spatial interpolation in predicting salinity.

3.3. Calculation of water storage capacity

Due to a lack of river topographic data, this study calculates water storage capacity based on dredging parameters using Equation 2. The parameters for dredging the canals were collected from the sub-department of Irrigation and Water Resources of Ben Tre province. The rivers and canals in Chau Thanh district, which have undergone dredging, would have a bottom elevation of -1.3 m (above the mean sea level at Hon Dau) and a trapezoidal cross-section, with the surface width equal to twice the bed width. These are the criteria for canal and river dredging in the district (Ben Tre Provincial People's Committee [Ben Tre PPC], 2018). The elevation in the district is flat and low-lying, with an average of approximately 1 m. Therefore, we select the water level of 0.5 m for water storage.

$$V = k.A.(h_s\text{-}h_b) \quad (2)$$

Where V is the storage capacity, k is the ratio of surface and bed widths. In Chau Thanh, k is 0.5 based on the dredging criteria of canals and rivers. A is the total water surface area. A was calculated using GIS-based geometry calculation. h_s is the storage water level, and h_b is the bed elevation.

4. RESULTS AND DISCUSSION

4.1. Current hydraulic infrastructures

The irrigation system of Chau Thanh district is situated within the Upper Ba Lai irrigation area. Currently, Chau Thanh district is developing and refining its hydraulic infrastructure to protect the entire district from saltwater intrusion originating from two primary branches of the Ham Luong River and the Tien River. However, the system remains incomplete, limiting its ability to fully control salinity intrusion.

The hydraulic infrastructure in Chau Thanh District currently comprises 13.2 km of level-1 canals, 79.4 km of embankments with an elevation of approximately 2.5 m, and nine sluices (three open sluices and six culverts, Figure 3). Additionally, the district is equipped with pumping stations to support irrigation demand. Despite these developments, the system is not fully enclosed, rendering it incapable of completely controlling saltwater intrusion. Chau Thanh experiences less severe saltwater intrusion in Ben Tre province, though its salinity levels fluctuate significantly with tidal variations.

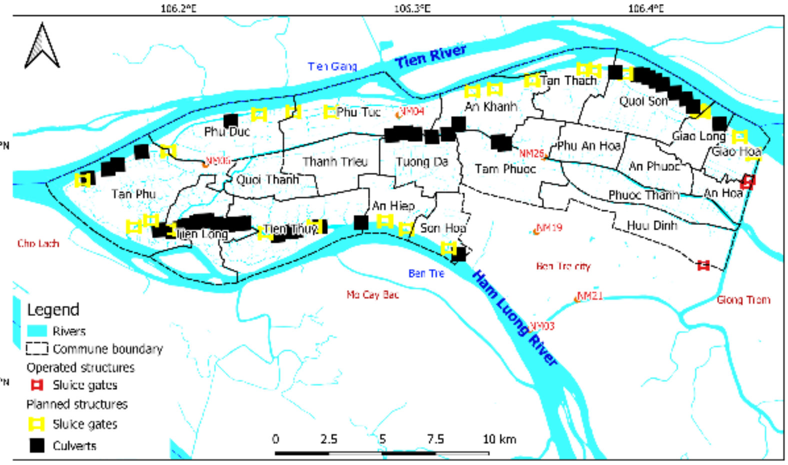

Figure 3. Hydraulic infrastructures in Chau Thanh district, Ben Tre province

In recent years, Chau Thanh has faced recurring droughts, particularly when combined with low Mekong River flows and deep saltwater intrusion, as observed in 2004, 2008, 2016, and 2020. Saltwater intrusion has shown a progressive trend of penetrating further inland. For instance, saltwater intrusion in 2008 was one of the strongest events. Then the saltwater intrusion of 2016 marked a deeper intrusion. The year 2020 is highlighted as a historic salinity event, with the 4‰ contour reaching the An Hoa sluice gate on the Ben Tre River. This sluice gate experiences an event once every 5 years, but now occurs annually. During the strongest saltwater intrusion in 2020, salinity exceeding 2‰ persisted at Cho Lach station from February to May, peaking at 6.7‰ and severely exacerbating freshwater scarcity in Chau Thanh district. Given the current state of its hydraulic infrastructure, the district remains vulnerable to severe saltwater intrusion due to incomplete closure of its hydraulic system.

4.2. Planned hydraulic infrastructures to control saltwater intrusion

To mitigate and adapt to saltwater intrusion in Chau Thanh district, the prioritized approach adopted is to use hard measures, focusing on the construction of salinity control structures. This strategy is outlined in the Ben Tre Provincial People's Committee (Ben Tre PPC, 2018). Such measures are widely implemented over the VMD. These structures will be built as part of a central government-funded project, with investment totaling trillions, to construct and upgrade coastal embankments and salinity-control sluices along the coastline from Quang Ngai to Ha Tien, as well as inland salinity-control sluices and culverts in coastal provinces affected by saltwater intrusion.

A key component of this strategy involves establishing and strengthening water regulation boards at the regional and provincial levels. These boards coordinate the operation of inter-district and inter-provincial sluices to balance water availability for brackish aquaculture while ensuring that freshwater zones remain unaffected. Additionally, the construction of embankment systems aims to protect residential areas and orchard zones, serving the dual purpose of preventing saltwater intrusion and mitigating flood risks (Ben Tre PPC, 2018) .

Figure 4. Bai Dac sluice gate constructed in 2020

The district has developed a comprehensive plan to construct a system of sluice gates and culverts to cope with saltwater intrusion, with implementation targeted for completion by 2030. The planned sluices are presented in Figure 3. Upon completion, this network of planned sluices, combined with existing structures in Ben Tre City, will form a closed system to safeguard agricultural production (primarily orchards). Several planned sluices, such as the Bai Dac sluice gate (see Figure 4), had already been constructed, marking progress toward the 2030 target.

4.3. Spatial interpolation performance

Table 1 indicates the model's prediction errors across variables, likely corresponding to different quantiles. Lower RMSE and MAE values suggest better model performance. Salinity at the 10th percentile exhibits the lowest RMSE (4.7 g/L) and a relatively low MAE (3.5 g/L), indicating better accuracy for this variable compared to Salinity at the 1st percentile and Salinity at the 50th percentile. Salinity at 1% percentile has the highest RMSE (6.6 g/L), suggesting larger prediction errors. Salinity at 50% percentile's RMSE (5.5 g/L) and MAE (3.4 g/L) are moderate.

A key limitation of the salinity interpolation model, based on data from 2011 to 2018, is its failure to capture the extreme salinity intrusion event in 2020. This event, driven by severe drought and reduced upstream freshwater flow, resulted in unprecedented saltwater intrusion. Therefore, the results may underestimate the spatial distribution of salinity.

Table 1. Cross-validation results for salinity interpolation

Salinity	RMSE (g/L)	MAE (g/L)
1% percentile	6.6	4.3
10% percentile	4.7	3.5
50% percentile	5.5	3.4

This study focuses on surface water salinity, which aligns with (Bui et al., 2025; Nguyen et al., 2018), targeting critical coastal challenges in the Mekong Delta. The interpolation's performance (RMSE = 4.7–6.6, MAE = 3.4–4.3) is less accurate than Nguyen et al. (RMSE = 4.17), primarily due to higher errors for high-salinity values and likely a smaller dataset.

4.4. Spatial distribution of saltwater intrusion without hydraulic system operation

4.4.1. Salinity Distribution of 1% percentile

The spatial analysis of saltwater intrusion at the 1st percentile reveals significant variability in affected areas across communes (Figure 5). Approximately 51% of the district's total area (11,600 ha) experiences severe salinity levels exceeding 4 g/L, impacting communes such as Quoi Son (1,548.7 ha), An Khanh (1,186.3 ha), and Huu Dinh (1,182.3 ha), posing substantial risks to agriculture and domestic water use. An additional 16% (3,700 ha) falls within the 2–4 g/L range, affecting areas like Phu Tuc (949.2 ha) and Thanh Trieu (782.6 ha), while 15% (3,300 ha) is subject to 0–2 g/L salinity, including Tien Thuy (1,046.5 ha) and Quoi Thanh (609.7 ha). Only 18% (4,100 ha) remains unaffected, primarily in Tan Phu (2,439.1 ha) and Phu Duc (764.1 ha), underscoring the critical need for targeted water management interventions to mitigate the impacts of saltwater intrusion.

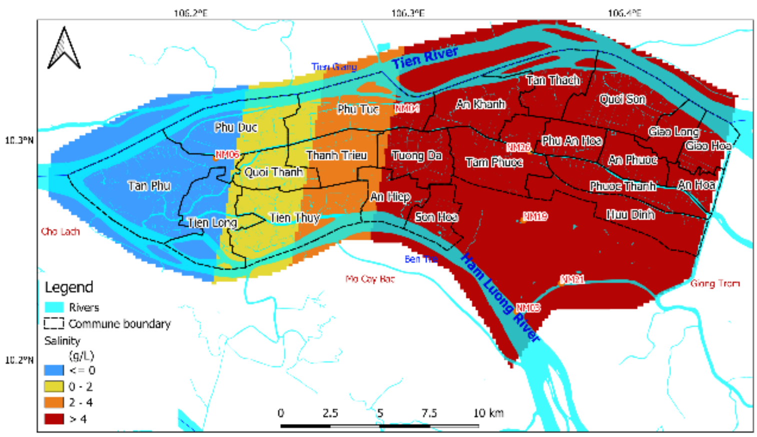

Figure 5. Spatial distribution of saltwater intrusion at 1% percentile

4.4.2. Salinity Frequency of 10% percentile

Figure 6 illustrates that during high-salinity years (10th percentile), approximately 33% of the Chau Thanh District area experiences saltwater intrusion with salinity exceeding 4 g/L. Affected communes include Giao Hoa, Giao Long, Huu Dinh, Phu An Hoa, Phuoc Thanh, Quoi Son, and parts of An Hoa, An Phuoc, Chau Thanh, Tan Phu, and Tan Thach.

Areas with salinity ranging from 2–4 g/L account for 18% of the district, encompassing An Khanh, Son Hoa, and portions of Tam Phuoc, Tuong Da, Tan Thach, An Hiep, Chau Thanh, and Phu Tuc. Salinity levels of 0–2 g/L affect 20% of the district, including most of Phu Tuc, Tien Thuy, Thanh Trieu, An Hiep, and a small part of Quoi Thanh. Areas unaffected by saltwater intrusion (29% of the district) include all of Phu Duc, Tan Phu, Tien Long, large parts of Tien Thuy and Phu Tuc, and a minor portion of Thanh Trieu. Thus, at a 10% salinity frequency, over 70% of Chau Thanh District is affected by saltwater intrusion, with Giao Hoa, Giao Long, Huu Dinh, Phu An Hoa, Phuoc Thanh, and Quoi Son experiencing salinity levels above 4 g/L, significantly hindering domestic and orchard irrigation.

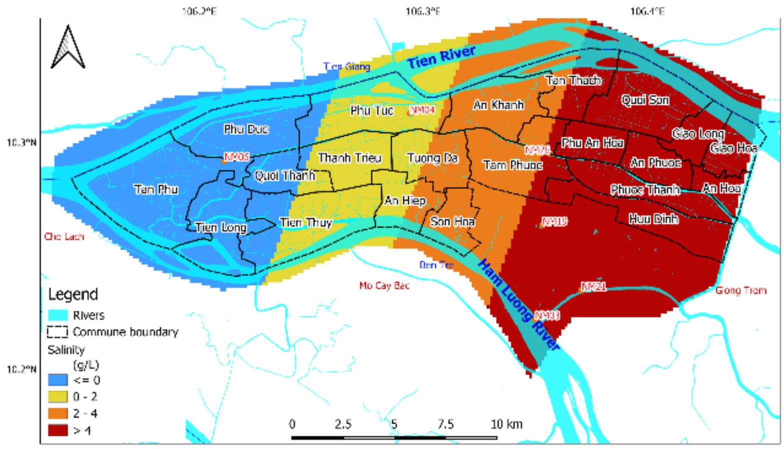

Figure 6. Spatial distribution of saltwater intrusion at 10% percentile

4.4.3. Salinity Frequency of 50% percentile

Figure 7 indicates that under average salinity conditions (50% frequency), corresponding to the representative year 2014, 16% of the district's area—comprising An Hoa, Giao Hoa, Giao Long, and parts of Huu Dinh, Phuoc Thanh, Quoi Son, and An Phuoc—experiences salinity above 4 g/L. Areas with salinity of 0–2 g/L cover 28% of the district, including all of Chau Thanh, Phu An Hoa, and most of Tan Thach, Tam Phuoc, Son Hoa, Quoi Son, Phuoc Thanh, Huu Dinh, An Phuoc, An Khanh, with a small portion of Tuong Da. Areas unaffected by saltwater intrusion account for 56% of the district, encompassing all of An Hiep, Phu Duc, Phu Tuc, Quoi Thanh, Thanh Trieu, Tien Long, Tien Thuy, Tan Phu, and parts of Tuong Da, Son Hoa, An Khanh, and Tam Phuoc. Thus, at a 50% salinity frequency, Chau Thanh district avoids high salinity levels (>4 g/L), with over 50% of its area unaffected by saltwater intrusion.

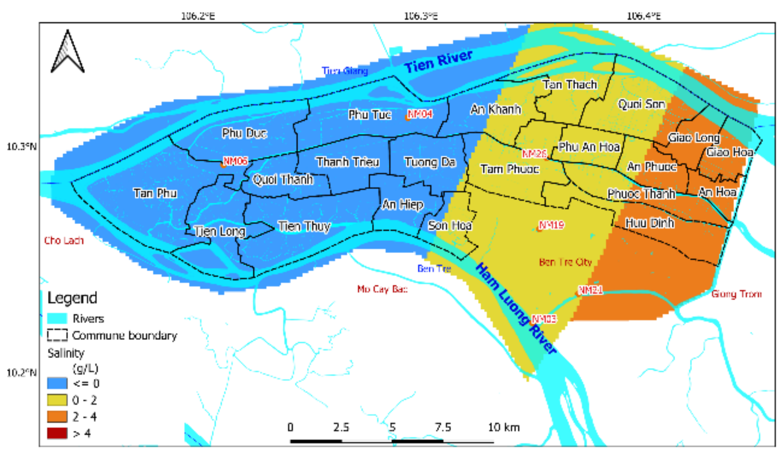

Figure 7. Spatial distribution of saltwater intrusion at 50% percentile

4.5. Proposed water management strategies

Drought poses a persistent natural hazard in the VMD, increasingly threatening water security. To proactively support agricultural production and sustainable development, the central government has invested in key infrastructure projects outlined in Decision No. 1397/QD-TTg by the Prime Minister, approving the *Mekong Delta Irrigation Plan for 2012–2020 with an Orientation to 2050* in the context of climate change and sea level rise. The proposed solutions primarily focus on hard-structural and technological measures.

As discussed previously and evaluated across three salinity risk scenarios (1%, 10%, and 50% percentiles), completing the planned salinity control sluice system to enclose the North Ben Tre irrigation zone will enable Chau Thanh to effectively manage saltwater intrusion from the Ham Luong and Tien rivers. A tailored sluice operation plan, aligned with hydrological conditions and salinity dynamics, will ensure freshwater availability for various purposes within the district. We proposed several options to deal with saltwater intrusion at 1%, 10%, and 50% percentiles under the planned hydraulic structures.

4.5.1. Water management under 1% percentile of salinity

In extreme scenarios of saltwater intrusion (1% percentile), we suggest applying several measures, including hard structures, water transfer, and water storage.

– Sluice gate operation: Only sluices in Tan Phu Commune can be opened to access freshwater, while all others must remain closed to prevent saltwater. This closure will challenge eastern communes (e.g., An Hoa) with limited freshwater for agriculture (e.g., orchard irrigation) and increased pollution within the control zone.

– Water transfer: A primary solution involves pumping water from Tan Phu to An Hoa via the Ba Lai River. Figure 8 shows operational pumping stations in Tan Phu. This pump supplies freshwater to orchards and rice fields via the canal network, particularly during low-flow seasons.

– Water storage: freshwater could be stored in canals and ditches by sourcing from Tan Phu along the Ba Lai River, supporting irrigation for agricultural crops and domestic use. Regional storage via temporary dams and household-scale storage will minimize water stress.

Figure 8. A pumping station for freshwater intake at Tan Phu commune

4.5.2. Water management under 10% percentile of salinity

During high-salinity years (10th percentile), saltwater intrusion affects up to 70% of the district. The remaining area can operate sluices strategically. Sluices in Phu Tuc, Phu Duc, Tan Phu, Tien Long, and Tien Thuy can be opened to release water, while others remain closed. Eastern communes face similar freshwater access and pollution issues as the 1% scenario. The Ba Lai River remains the main conduit for transfer and storage, supplemented by dredging of level-1, -2, and -3 canals and the construction of temporary salinity barriers. The network of sluices operated requires monitoring of salinity and water levels in rivers, with daily updates via radio and television broadcasts to inform residents of sluice schedules and water conditions for proactive irrigation planning.

4.5.3. Water management under 50% percentile of salinity

In average salinity years (50% percentile), most of Chau Thanh remains unaffected. Attention focuses on vulnerable communes of Phu An Hoa, Quoi Son, An Phuoc, Giao Long, Giao Hoa, An Hoa, Phuoc Thanh, and Huu Dinh, The others easily access freshwater from the Tien and Ham Luong rivers.

5. CONCLUSION

Due to its geographical position between two major rivers and its relatively inland location compared to other districts in Ben Tre Province, Chau Thanh experiences less severe saltwater intrusion. Although not entirely a freshwater zone, surface water resources generally meet most demands for agricultural production and domestic use. Research findings based on natural conditions (excluding irrigation system operations) indicate that in extreme drought scenarios (100-year, 1%

frequency), approximately 50% of the district's area is at risk of salinity exceeding 4 g/L. In typical years (occurring once every two years, 50% frequency), about 16% of the district faces salinity risks above 4 g/L. Notably, eastern communes are more severely affected than other areas. While existing salinity control structures demonstrate localized effectiveness, their incomplete closure allows saltwater intrusion to impact certain areas during dry seasons. Completing the irrigation system for freshwater transfer and storage, along with regular dredging of internal canals, is essential to secure freshwater for irrigation and flush residual salts in canals. The salinity control infrastructure must be urgently constructed and finalized to achieve complete salinity management. However, even with effective salinity control, freshwater shortages may arise when sluice gates are completely closed during dry seasons. Planning for water storage zones is critical to ensure a sufficient supply for agricultural irrigation and domestic purposes.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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