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MEKONG DELTA SALINITY RISK ASSESSMENT USING SPATIAL ANALYSIS AND THE IYENGAR-SUDARSHAN METHOD

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Abstract

Saltwater intrusion has become a significant problem in coastal regions across the globe, including Vietnam, impacting resident livelihoods, economies, and societies. Particularly, the Mekong Delta region plays a pivotal role in Vietnam's economy and agriculture, serving as a crucial source for Vietnam's socio-economic development and environmental sustainability. Salinity risk assessment maps can provide information on risk levels based on salinity intrusion hazard, exposure, and vulnerability, facilitating the evaluation of saltwater intrusion impacts on specific areas. To respond to this gap, this study applied the Iyengar-Sudarshan method and spatial analysis techniques to assess the risk of salinity intrusion at the district scale for some provinces in the Mekong Delta, utilizing the holistic risk assessment framework outlined by the Intergovernmental Panel on Climate Change. The results indicate that the regions with the highest salinity risk are Ba Tri, Binh Dai and Thanh Phu districts of Ben Tre province, and Tan Phu Dong district of Tien Giang province. Vinh Long Hau Giang, and a section of Tien Giang province adjacent to Dong Thap province exhibit the lowest salinity risk Vinh Long and Hau Giang provinces are identified as areas without salinity risk. The results obtained from this study may aid in formulating strategies to adapt to saltwater intrusion and improving sustainable measures to mitigate the adverse effects of salinity intrusion.

Keywords: risk; salinity intrusion; Iyengar-Sudarshan method; GIS; Mekong Delta.

1. Introduction

In recent years, climate change has created unusual and irregular weather patterns, of which drought and saltwater intrusion are considered a significant challenge for coastal countries due to their severity and potential impacts on life, economy, and society. Salinity intrusion threatens domestic water sources, human health, livelihoods, infrastructure, and economic development, contributing to poverty and widespread migration [1]. In Vietnam, the salinity intrusion has occurred mainly in the Mekong Delta region [2], as evidenced by the severe drought in 2016, which degraded 22% of the rice area, equivalent to 12% of the country's rice output and 8% of its agricultural output, directly jeopardizing the livelihoods of about 3 million farmers [3]. According to the National Center for Hydrometeorological Forecasting, in the dry season of 2023–2024, saltwater intrusion in the Mekong Delta has continued at a higher level than the average for many years, equivalent to 2020–2021 [4]. The Mekong Delta is home to half of the country's population. It is still a place with a rapid urbanization rate, bringing many opportunities to develop tourism, agriculture, industry, and other sectors,

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helping to maintain and diversify sources of livelihood to reduce poverty and attract an amount of labour to this area [3].

Salinity intrusion is not an environmental problem but a comprehensive challenge to human life, economy, and society. Because of their spatial information about potential salinity areas, salinity intrusion predictive maps have been considered an effective tool in managing and preventing saltwater intrusion. Meanwhile, the salinity risk zoning map can provide accurate and timely information to local authorities and communities to develop long-term plans to respond to salinity intrusion and strengthen responsibility and community participation in addressing challenges related to climate change [5].

Climate change contributes to the increase of salinity intrusion in coastal areas worldwide. Thus, there are many approaches to assessing natural disasters, including risk is considered a combination of hazards and their potential consequences [6–9], or risk is regarded as a combination of hazard, exposure, and vulnerability [10–13]. According to the Intergovernmental Panel on Climate Change (IPCC), the risk is the possibility of severe changes in the normal functioning of a community or society at a given time, leading to widespread adverse effects on humans, the economy, and the environment. It requires an immediate response to adapt to human needs and external assistance for recovery [13]. The risk is a process that changes over time and space [14]; meanwhile, the risk framework based on the hazard, exposure, and vulnerability of IPCC (2012) not only identifies the scope of impact of the salinity hazard but also measures the exposure and vulnerability levels, consisting of present and potential challenges [10, 14]. Consequently, the IPCC's framework for assessing natural disaster risks to climate change is considered a comprehensive approach that allows effective understanding and response to saltwater intrusion [15]. Generally, the IPCC's framework has been applied successfully in studies related to flood risk assessment [16, 17] and landslide risk assessment [18, 19], but has not been widely applied in salinity risk assessment.

Nowadays, Geographic Information System (GIS) is a powerful technology that integrates information from various sources and facilitates spatial analyses to identify trends, correlations, and environmental changes. Thus, this technology can be applied independently in salinity risk assessment studies [5, 20] or combined with other methods, such as GALDIT, GQI_{SWI} in salinity risk assessment [21]. Moreover, the Iyengar-Sudarshan method is an advanced approach for evaluating and processing data in decision-making analysis problems. Instead of treating all influencing factors equally, this method assigns weight to each factor based on its importance, leading to increased accuracy in risk assessment and decision-making [22]. This method can effectively handle quantitative and qualitative data, making it flexible and suitable for various data sources and fields [23]. However, the Iyengar-Sudarshan and GIS methods have primarily been applied in a few vulnerability assessment studies [24, 25] and have not been widely employed in assessing salinity risk based on the IPCC framework.

The Mekong Delta is crucial in Vietnam's economic development, defence, and foreign affairs. Covering an area of about 39,734 km^2, which accounts for 12.2% of the country's total area, the Mekong Delta is currently home to approximately 18 million people, representing 19% of the country's population. Several studies have been conducted to assess the salinity risk for each province, such as Ben Tre province [26–28], Tra Vinh province [29] or the whole region [30–32] by using remote sensing, GIS, and artificial intelligent models. The latest study by Le, et al. [33] assessed the salinity risk for the Mekong Delta region by combining the hazard, exposure, and vulnerability of the IPCC framework; however, this study only evaluated the salinity risk at the provincial scale.

Therefore, this study used the Iyengar-Sudarshan and GIS methods to assess salinity risk at the district level based on the holistic risk assessment framework of the IPCC (2012). This study's results can provide detailed and accurate information about the salinity risk and enable a comprehensive assessment of the impact and the subjects susceptible to the negative impacts of saltwater intrusion risk at the district level. Furthermore, these findings also establish a robust theoretical basis, facilitating a comprehensive understanding of the salinity risk for the coastal areas of the Mekong Delta region.

2. Materials and Methods

2.1. Study area

The research area comprises six provinces: Tien Giang, Vinh Long, Hau Giang, Ben Tre, Tra Vinh, and Soc Trang. This area spans the entire Mekong River in Vietnam, which was significantly influenced by salinity intrusion. During the flood season from July to November, the salinity intrusion is mainly concentrated in river estuaries. However, the salinity intrusion encroaches into the land during the dry season from December to June of the following year (Fig. 1).

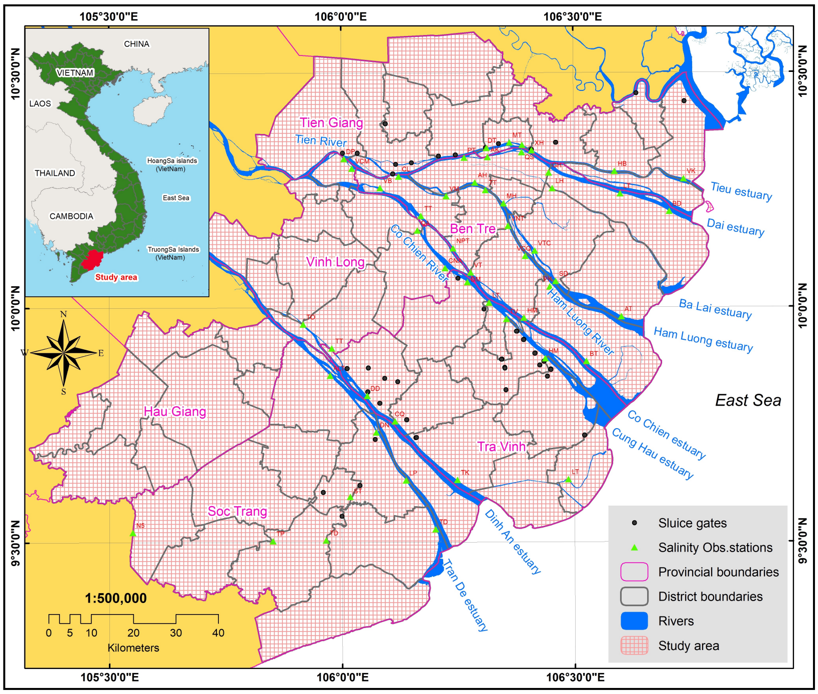

Figure 1. The research area

2.2. Theoretical framework for salinity risk assessment

a. Theoretical basis

In this study, the Intergovernmental Panel on Climate Change (IPCC) risk assessment framework is applied to assess the salinity risk [34, 35]. Accordingly, the risk is the combination of three factors, including Hazard (H), Exposure (E), and Vulnerability (V), expressed by the following equations

$$\mathrm{R} = f(\mathrm{H} \times \mathrm{E} \times \mathrm{V}) \tag{1}$$

$$\mathrm{V} = f(\mathrm{S} \times \mathrm{AC}) \tag{2}$$

where H is the salinity hazard, E denotes the salinity exposure, V expresses the salinity vulnerability, S describes the salinity sensitivity, and AC represents the salinity adaptive capacity.

b. Methodology

In this study, the salinity intrusion risk assessment is conducted by applying the Iyengar-Sudarshan and GIS techniques according to the risk assessment framework of the IPCC (2012). Risk is evaluated by combining three components: hazard, exposure, and vulnerability. The saltwater intrusion hazard map was built using in-situ data from salinity monitoring stations in 2020. The salinity exposure criteria include two main factors: agriculture and population. Vulnerability is considered by combining sensitivity and adaptive capacity, in which sensitivity is evaluated by using six main criteria (population, gender, agriculture, people, geographical location, and natural conditions), and adaptability is assessed based on five key criteria (population, education, socio-economic, production, health, and disaster prevention).

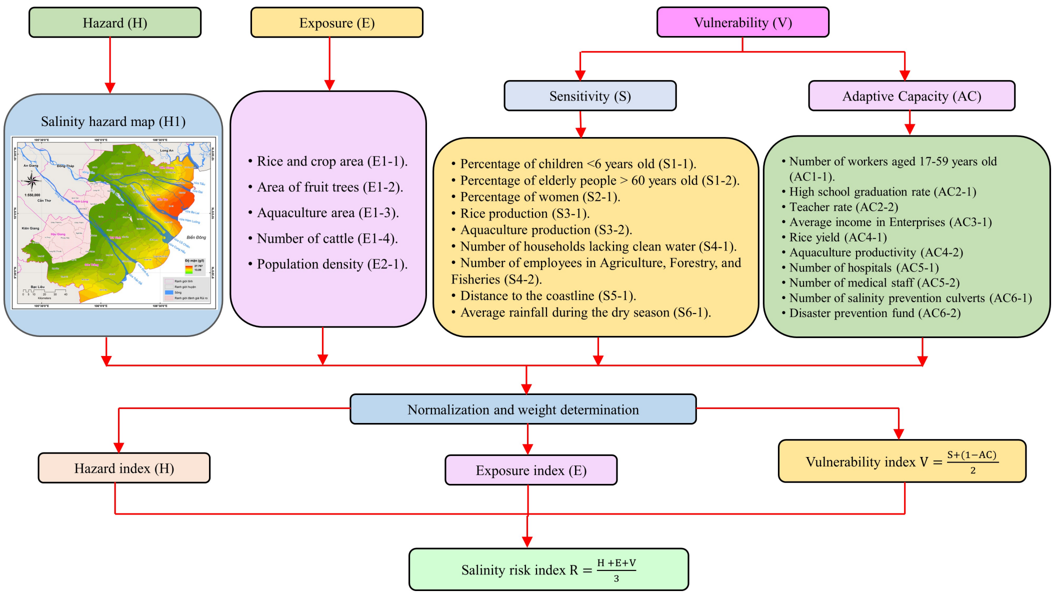

Figure 2. The methodology applied in this research

All criteria representing hazard, exposure, and vulnerability components will be normalized using the min-max method. Subsequently, the Iyengar-Sudarshan method will be applied to determine the weight of each component factor. Finally, all component factors will be overlaid with their corresponding weight values in the GIS environment to construct a salinity risk zoning map. The flowchart of this study is presented in Fig. 2.

c. Selection of criteria for salinity risk assessment

- Determination of the salinity hazard

The "hazard" term (H) in this context refers to the occurrence of unfavourable natural or human-induced phenomena capable of causing harm to people, impacting health, and causing damage to property, infrastructure, and livelihoods [13]. The salinity hazard often depends on the frequency, intensity, speed, duration, and extent of saltwater intrusion. In this study, in-situ data from 52 salinity monitoring stations and 48 salinity prevention culverts across six provinces in the Mekong Delta on February 23, 2020 was collected and interpolated to generate a salinity intrusion hazard map. The position of salinity monitoring stations and prevention culverts were collected by using the GNSS technology through field surveys in 2019, 2020, and 2022.

- Determination of the salinity exposure

Exposure (E) is defined as the geographical presence of people, livelihoods, environmental services, resources, infrastructure, or other economic, social, or cultural assets in areas that might be adversely affected by natural phenomena [13]. The incursion of salinity substantially affects the inhabitants and their means of living in the Mekong Delta, especially in areas where agriculture is the customary source of income for local residents [36]. Therefore, the salinity exposure data encompasses two factors: human and agriculture (Table 1).

Table 1. Selection of exposure criteria to salinity intrusion hazard

Component	Main criteria	Sub-criteria	Detail level	Unit	Source
Exposure (E)	Agriculture E1	Rice and crop area (E1-1)	District scale	ha	Mekong Delta statistical yearbook 2020
		Area of fruit trees (E1-2)	District scale	ha	
		Aquaculture area (E1-3)	District scale	ha	
		Number of cattle (E1-4)	District scale	Thousand	
	Human E2	Population density (E2-1)	District scale	Person/km^2	

- Determination of the salinity vulnerability:

Vulnerability (V) refers to the tendency of sensitivity factors to the salinity hazard, such as people and properties. According to IPCC (2012), the salinity vulnerability includes Sensitivity (S) and adaptive capacity (AC). Sensitivity (S) reflects the degree to which a system is affected (positively or negatively) by one or more impacts; these impacts can be from internal or external impacts. Adaptive Capacity (AC) signifies the response-ability of a system to the salinity vulnerability. Adaptive capacity pertains to the access ability to natural resources, financial capacity, infrastructure, political institutions, human resources, and social relationships [13].

In this study, the salinity vulnerability criteria include 12 main criteria and 19 sub-criteria representing two components, including "Sensitivity-S" and "Adaptive capacity-AC" (Table 2).

Table 2. Selection of vulnerability criteria to salinity intrusion hazard

Component	Main criteria	Sub-criteria	Detail level	Unit	Source
Sensitivity (S)	Population (S1)	Percentage of children < 6 years old (S1-1)	District scale	%	Department of Dyke Management and Disaster Prevention
		Percentage of elderly people > 60 years old (S1-2)	District scale	%	
	Gender (S2)	Percentage of women (S2-1)	District scale	%	
	Agriculture (S3)	Rice production (S3-1)	District scale	Ton	Mekong Delta statistical yearbook 2020
		Aquaculture production (S3-2)	District scale	Ton	
	Human (S4)	Number of households lacking clean water (S4-1)	District scale	Household	Department of Dyke Management and Disaster Prevention
		Number of employees in Agriculture, Forestry, and Fisheries (S4-2)	District scale	Person	Mekong Delta statistical yearbook 2020
	Geographical locations (S5)	Distance to the coastline (S5-1)	District scale	Km	Field survey
	Natural conditions (S6)	Average rainfall during the dry season (S6-1)	District scale	mm	Hydrometeorological center

Component	Main criteria	Sub-criteria	Detail level	Unit	Source
Adaptive Capacity (AC)	Population (AC1)	Number of workers aged 17-59 years old (AC1-1)	District scale	Person	Department of Dyke Management and Disaster Prevention
	Education (AC2)	High school graduation rate (AC2-1)	District scale	%	Mekong Delta statistical yearbook 2020
		Teacher rate (AC2-2)	District scale	/1000 person	
	Socio-economic (AC3)	Average income in Enterprises (AC3-1)	District scale	Million VND	
	Production (AC4)	Rice yield (AC4-1)	District scale	Ton/ha	
		Aquaculture productivity (AC4-2)	District scale	Ton/ha	
	Medicine (AC5)	Number of hospitals (AC5-1)	District scale	Hospital	
		Number of medical staff (AC5-2)	District scale	Person	
	Disaster prevention (AC6)	Number of salinity prevention culverts (AC6-1)	District scale	Culvert	Department of Dyke Management and Disaster Prevention
		Disaster prevention fund (AC6-2)	District scale	Billion VND	

2.3. Methods used

a. Normalization method

Since the units of the criteria representing hazard (H), exposure (E), and vulnerability (V) components are different, it is necessary to convert them into the same rating scale, which can be [0, 1] or [−1, 1]. There are various normalization methods, such as the Box-Cox normalization technique [37], min-max normalization technique [38, 39], data standardization technique [39], and data normalized technique [40]. The min-max normalization method is relatively simple and easy to understand. It does not require many complex calculations, which makes this method a popular choice and easy to conduct in real applications. Thus, this study uses the min-max normalization method to standardize data by applying the following equations:

- If there is a co-variant relationship between criteria and salinity risk, the standardized value is calculated according to formula (3):

$$y_{ij} = \frac{X_{ij} - \min X_{ij}}{\max X_{ij} - \min X_{ij}} \tag{3}$$

- If the relationship between criteria and risk is inverse, the standardized value is determined using formula (4):

$$y_{ij} = \frac{\min X_{ij} - X_{ij}}{\max X_{ij} - \min X_{ij}} \tag{4}$$

where y_{ij} is the normalized value; X_{ij} denotes is the initial value of sub-criterion j in main criterion i; $\max X_{ij}$, $\min X_{ij}$ represent the maximum and minimum values of sub-criterion j in main criterion i.

After normalization, all data values (y_{ij}) will be within the range of 0 to 1.

b. The Iyengar-Sudarshan method

The Iyengar-Sudarshan method is convenient for calculating weights for various variables or multiple sub-criteria within a primary criterion [22]. This method evaluates the importance of sub-criteria that directly contribute to the main criteria representing hazard (H), exposure (E), and vulnerability

(V). Accordingly, the calculated weights ensure that no single criterion will be over-dominated by the remaining criteria. Furthermore, this method also uses the standard deviation in calculating the weight for each criterion, leading to accuracy and effectiveness for the obtained results. Mathematically, the content of this technique can be summarized below [22]:

- Calculate the temporary weight of each sub-criterion using formula (5):

$$w_j = \frac{C}{\sqrt{\text{Var}\left(y_{ij}\right)}} \tag{5}$$

where w_j represents the weight of the sub-criterion in the j^{th} main criterion of the E, S, and AC component criteria; y_{ij} is the standardized value in formula (3) or formula (4); and C is determined by formula (6):

$$C = \left[\sum_{j=1}^{K} \frac{1}{\sqrt{\text{Var}\left(y_{ij}\right)}}\right]^{-1} \tag{6}$$

where K represents the sub-criteria in the main criteria of the E, S, or AC component criteria.

- Var represents the variance of the sub-criteria, calculated by using formula (7):

$$\text{Var} = \frac{1}{m-1} \sum_{i=1}^{m} \left(y_{ij} - \bar{y}_{ij}\right)^2 \tag{7}$$

- $\bar{y}_{ij}$ is the average value and calculated by using formula (8):

$$\bar{y}_{ij} = \frac{1}{m} \sum_{i=1}^{m} y_{ij} \tag{8}$$

where m is the number of administrative units within the study area.

The value of the main criteria is calculated according to formula (9):

$$M = \frac{\sum_{i=1}^{n} w_{ij} y_{ij}}{n} \tag{9}$$

where M represents the value of the main criteria for exposure (E), sensitivity (S), and adaptability (AC); n is the sum of sub-criteria within a main criterion; w_{ij} is the weight of the sub-criteria calculated according to formula (5).

After determining the value of the main criteria according to formula (9), the indexes of the E, S, and AC component criteria are calculated as below:

$$CF = \frac{\sum_{i=0}^{N} v_{M_i} M_i}{\sum_{i=0}^{N} v_{M_i}} \tag{10}$$

where CF represents the index of the E, S, and AC component criteria; N is the number of main criteria in the E, S, and AC component criteria; v is the number of sub-criteria in a main criterion; M_i is the value of the i^{th} main criterion calculated according to formula (9).

3. Results and discussions

3.1. Construction of the salinity intrusion hazard map

In this study, the location of salinity monitoring stations and prevention culverts were collected by using the GNSS technology through field surveys in 2019, 2020, and 2022. Based on in-situ data gathered from 52 salinity monitoring stations and 48 salinity prevention culverts across six provinces in the Mekong Delta on February 23, 2020, the salinity intrusion hazard was generated by using the IDW spatial interpolation in ArcGIS 10.8 software (Fig. 3). Ben Tre, Tra Vinh, and Soc Trang provinces are adjacent to the East Sea; however, the river and canal density in the Ben Tre province is higher than that of the two remaining provinces. According to that, the interpolation results exhibited that the Ba Tri district and Binh Dai district of the Ben Tre province are situated in the highest salinity with a value of 27,767 g/l (Fig. 3).

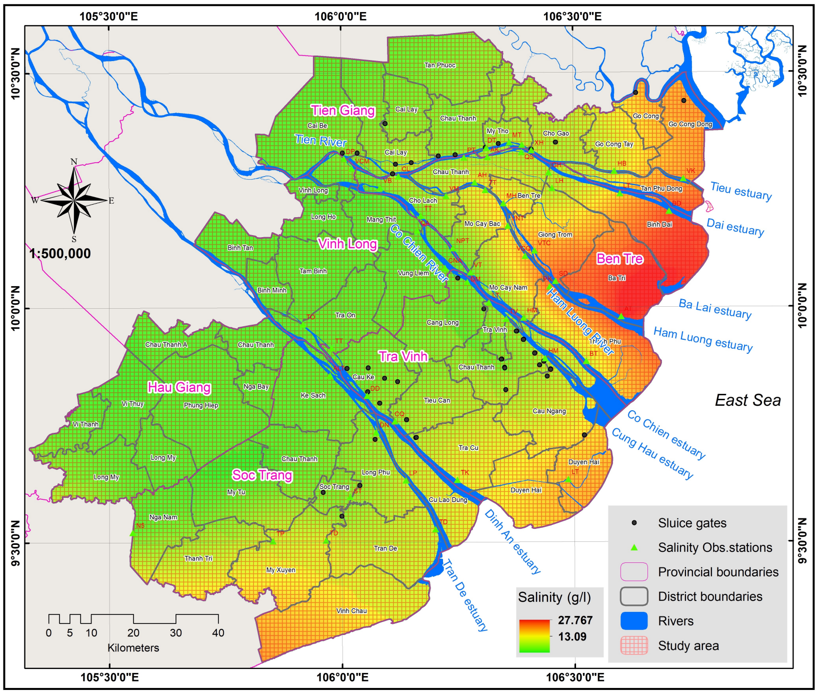

Figure 3. The salinity hazard map on February 23, 2020

3.2. Construction of the exposure map to salinity intrusion

The normalization and weight determination results of criteria representing the salinity exposure are shown in Table 3.

Table 3. The normalization and weight determination results of salinity exposure criteria

Provinces	Districts	Criteria of exposure E				
		E1				E2
		E1-1	E1-2	E1-3	E1-4	E2-1
Ben Tre	Ben Tre	0.01	0.25	0.00	0.02	0.59
	Ba Tri	0.54	0.24	0.17	0.08	0.13
	Binh Dai	0.13	0.54	0.66	0.06	0.07

Provinces	Districts	Criteria of exposure E				
		E1				E2
		E1-1	E1-2	E1-3	E1-4	E2-1
	Cho Lach	0.00	0.56	0.00	0.05	0.19
	Chau Thanh	0.00	0.81	0.02	0.09	0.23
	Giong Trom	0.16	1.00	0.02	0.25	0.14
	Mo Cay Bac	0.02	0.63	0.00	0.56	0.19
	Mo Cay Nam	0.03	0.83	0.02	1.00	0.17
	Thanh Phu	0.18	0.41	0.61	0.10	0.06
Hau Giang	Chau Thanh	0.00	0.53	0.01	0.00	0.17
	Chau Thanh A	0.29	0.22	0.02	0.00	0.17
	Long My	0.61	0.23	0.04	0.01	0.05
	Long My (town)	0.35	0.12	0.03	0.00	0.03
	Nga Bay	0.08	0.18	0.01	0.00	0.21
	Phung Hiep	1.00	0.41	0.14	0.01	0.08
	Vi Thanh	0.20	0.17	0.00	0.00	0.17
	Vi Thuy	0.55	0.17	0.02	0.00	0.08
Soc Trang	Chau Thanh	0.59	0.02	0.04	0.03	0.09
	Cu Lao Dung	0.30	0.07	0.14	0.00	0.03
	Ke Sach	0.38	0.38	0.08	0.01	0.10
	Long Phu	0.54	0.06	0.03	0.01	0.07
	My Tu	0.82	0.04	0.12	0.00	0.03
	My Xuyen	0.92	0.01	0.68	0.00	0.09
	Nga Nam	0.61	0.02	0.10	0.00	0.05
	Soc Trang	0.13	0.02	0.01	0.00	0.61
	Thanh Tri	0.76	0.01	0.14	0.00	0.03
	Tran De	0.80	0.01	0.20	0.01	0.05
	Vinh Chau	0.13	0.03	1.00	0.00	0.07
Tien Giang	Cai Be	0.53	0.79	0.04	0.01	0.20
	Cai Lay	0.19	0.24	0.02	0.01	0.45
	Cai Lay (town)	0.30	0.68	0.00	0.00	0.10
	Cho Gao	0.08	0.73	0.00	0.13	0.24
	Chau Thanh	0.20	0.59	0.01	0.01	0.36
	Go Cong	0.18	0.00	0.02	0.01	0.31
	Go Cong Dong	0.46	0.01	0.11	0.02	0.16
	Go Cong Tay	0.39	0.07	0.03	0.02	0.20
	My Tho	0.01	0.25	0.00	0.01	0.97
	Tan Phu Dong	0.06	0.17	0.24	0.00	0.04
	Tan Phuoc	0.25	0.72	0.00	0.01	0.01
Tra Vinh	Cau Ke	0.36	0.52	0.02	0.01	0.09
	Cau Ngang	0.66	0.15	0.25	0.01	0.08
	Cang Long	0.52	0.55	0.03	0.01	0.13

Provinces	Districts	Criteria of exposure E				
		E1				E2
		E1-1	E1-2	E1-3	E1-4	E2-1
	Chau Thanh	0.63	0.27	0.18	0.01	0.08
	Duyen Hai	0.12	0.10	0.47	0.00	0.05
	Duyen Hai (town)	0.04	0.04	0.37	0.00	0.00
	Tieu Can	0.50	0.31	0.01	0.01	0.22
	Tra Cu	0.79	0.23	0.05	0.01	0.11
	Tra Vinh	0.05	0.13	0.00	0.00	0.55
Vinh Long	Binh Minh	0.10	0.21	0.00	0.01	0.32
	Binh Tan	0.33	0.14	0.00	0.01	0.17
	Long Ho	0.22	0.38	0.01	0.01	0.26
	Mang Thit	0.15	0.36	0.01	0.03	0.16
	Tam Binh	0.55	0.41	0.02	0.02	0.13
	Tra On	0.39	0.52	0.01	0.02	0.12
	Vinh Long	0.01	0.12	0.00	0.00	1.00
	Vung Liem	0.46	0.54	0.01	0.03	0.12
	Var	0.072	0.068	0.041	0.023	0.042
	$\frac{1}{\sqrt{\text{Var}}}$	3.758	3.867	4.972	6.590	4.914
	w_j	0.196	0.202	0.259	0.020	1.00

The salinity exposure map was built in the ArcGIS 10.8 environment, Fig. 4.

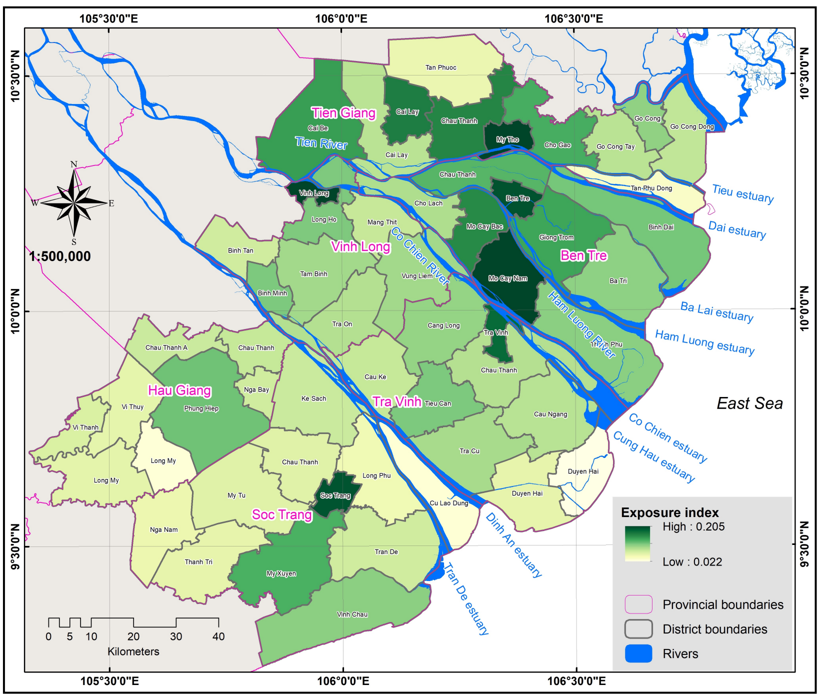

Figure 4. The salinity exposure map

The results reveal that areas with high salinity exposure are concentrated in urban areas of provinces, including Vinh Long city in Vinh Long province, Soc Trang city, My Tho city, Ben Tre city, and Mo Cay Nam district in Ben Tre province. On the other hand, districts such as Cu Lao Dung, Tan Phu Dong, and the towns of Long My and Duyen Hai exhibit low salinity exposure.

3.3. *Construction of the vulnerability map to salinity intrusion*

This study assesses vulnerability by combining two factors: Sensitivity (S) and Adaptive Capacity (AC). The results of standardization and weight determination for criteria representing salinity sensitivity are presented in Table 4.

Table 4. The normalization and weight determination results of salinity sensitivity criteria

Provinces	Districts	Criteria of sensitivity S								
		S1		S2	S3		S4		S5	S6
		S1-1	S1-2	S2-1	S3-1	S3-2	S4-1	S4-2	S5-1	S6-1
Ben Tre	Ben Tre	0.18	0.73	0.40	0.00	0.00	0.00	0.52	0.46	0.01
	Ba Tri	0.52	0.61	0.57	0.08	0.79	0.68	0.71	0.00	0.80
	Binh Dai	0.44	0.62	0.40	0.01	1.00	0.73	0.37	0.00	0.38
	Cho Lach	0.41	0.77	0.30	0.00	0.27	0.35	0.33	0.67	0.00
	Chau Thanh	0.24	0.72	0.61	0.00	0.25	0.19	0.49	0.55	0.31
	Giong Trom	0.40	0.89	0.52	0.01	0.14	0.41	0.60	0.31	0.27
	Mo Cay Bac	0.50	0.83	0.31	0.00	0.00	0.54	0.39	0.50	0.07
	Mo Cay Nam	0.43	1.00	0.41	0.00	0.14	0.33	0.58	0.37	0.20
	Thanh Phu	0.60	0.61	0.35	0.05	0.23	0.54	0.36	0.00	0.67
Hau Giang	Chau Thanh	0.39	0.50	0.22	0.00	0.06	0.00	0.16	0.71	0.35
	Chau Thanh A	0.55	0.58	0.25	0.38	0.04	0.00	0.27	0.63	0.49
	Long My	0.63	0.61	0.16	0.68	0.03	0.00	0.10	0.57	0.22
	Long My (town)	0.54	0.78	0.02	0.38	0.02	0.00	0.18	0.60	0.31
	Nga Bay	0.60	0.52	0.09	0.02	0.09	0.00	0.29	0.64	0.05
	Phung Hiep	0.57	0.56	0.58	0.75	0.12	0.00	0.48	0.72	0.20
	Vi Thanh	0.73	0.41	0.16	0.15	0.02	0.00	0.35	0.45	0.14
	Vi Thuy	0.65	0.64	0.21	0.75	0.03	0.00	0.21	0.55	0.20
Soc Trang	Chau Thanh	0.71	0.59	0.22	0.63	0.03	0.17	0.17	0.45	0.50
	Cu Lao Dung	0.61	0.57	0.09	0.00	0.13	0.53	0.11	0.00	0.52
	Ke Sach	0.51	0.66	0.43	0.36	0.08	0.93	0.40	0.52	0.20
	Long Phu	0.79	0.76	0.21	0.45	0.05	0.30	0.18	0.27	0.69
	My Tu	0.92	0.69	0.19	0.91	0.09	0.57	0.13	0.43	0.58
	My Xuyen	0.36	0.52	0.45	0.34	0.22	0.15	0.27	0.23	0.88
	Nga Nam	0.57	0.54	0.15	0.62	0.08	0.61	0.14	0.44	0.47
	Soc Trang	0.41	0.48	0.43	0.08	0.00	0.00	0.54	0.32	1.00
	Thanh Tri	0.98	0.65	0.13	1.00	0.07	0.35	0.10	0.31	0.82
	Tran De	0.87	0.55	0.28	0.56	0.50	0.60	0.21	0.00	0.81
	Vinh Chau	0.76	0.39	0.48	0.03	0.47	0.41	0.26	0.00	0.90
	Cai Be	0.42	0.57	1.00	0.54	0.28	0.00	0.83	1.00	0.13
	Cai Lay	0.52	0.59	0.61	0.32	0.23	0.00	0.43	0.77	0.01

Provinces	Districts	Criteria of sensitivity S								
		S1		S2	S3		S4		S5	S6
		S1-1	S1-2	S2-1	S3-1	S3-2	S4-1	S4-2	S5-1	S6-1
	Cai Lay (town)	0.40	0.70	0.36	0.13	0.04	0.00	0.44	0.83	0.00
	Cho Gao	0.40	0.64	0.61	0.01	0.03	1.00	0.34	0.40	0.48
	Chau Thanh	0.35	0.50	0.95	0.10	0.03	0.00	0.56	0.61	0.07
	Go Cong	0.50	0.54	0.26	0.13	0.06	0.51	0.23	0.00	0.13
	Go Cong Dong	0.61	0.51	0.40	0.23	0.56	0.72	0.24	0.00	0.11
	Go Cong Tay	0.41	0.70	0.36	0.24	0.05	0.69	0.11	0.22	0.10
	My Tho	0.27	0.57	0.85	0.00	0.44	0.00	1.00	0.50	0.42
	Tan Phu Dong	0.70	0.52	0.03	0.00	0.17	0.23	0.00	0.00	0.13
	Tan Phuoc	0.73	0.29	0.13	0.23	0.01	0.00	0.04	0.69	0.07
Tra Vinh	Cau Ke	0.75	0.74	0.25	0.32	0.03	0.03	0.35	0.44	0.42
	Cau Ngang	0.76	0.66	0.32	0.29	0.24	0.67	0.47	0.15	0.00
	Cang Long	0.64	0.74	0.43	0.45	0.04	0.30	0.50	0.51	0.57
	Chau Thanh	0.88	0.56	0.42	0.45	0.12	0.84	0.37	0.00	0.22
	Duyen Hai	0.80	0.40	0.17	0.03	0.17	0.39	0.18	0.00	0.44
	Duyen Hai (town)	0.51	0.25	0.00	0.00	0.17	0.17	0.16	0.00	0.40
	Tieu Can	0.00	0.00	0.29	0.39	0.03	0.56	0.27	0.29	0.44
	Tra Cu	1.00	0.54	0.41	0.31	0.38	0.76	0.49	0.14	0.42
	Tra Vinh	0.28	0.41	0.37	0.02	0.03	0.00	0.49	0.38	0.13
Vinh Long	Binh Minh	0.45	0.47	0.26	0.09	0.03	0.00	0.29	0.93	0.52
	Binh Tan	0.52	0.48	0.24	0.15	0.13	0.00	0.29	0.84	0.78
	Long Ho	0.39	0.63	0.54	0.24	0.22	0.00	0.52	0.88	0.18
	Mang Thit	0.46	0.80	0.24	0.26	0.11	0.00	0.26	0.74	0.06
	Tam Binh	0.55	0.73	0.45	0.62	0.08	0.00	0.51	0.85	0.33
	Tra On	0.53	0.88	0.36	0.28	0.10	0.00	0.41	0.61	0.37
	Vinh Long	0.31	0.59	0.44	0.01	0.01	0.00	0.79	0.93	0.05
	Vung Liem	0.48	0.95	0.43	0.50	0.13	0.00	0.60	0.61	0.43
	Var	0.040	0.029	0.043	0.069	0.038	0.093	0.042	0.089	0.071
	$\frac{1}{\sqrt{\text{Var}}}$	4.985	5.873	4.823	3.802	5.101	3.279	4.886	3.358	3.745
	w_{ij}	0.459	0.541	1.000	0.427	0.573	0.402	0.598	1.00	1.00

The salinity sensitivity map was generated in the ArcGIS 10.8 environment, Fig. 5.

The results show that the areas with high salinity sensitivity are Cho Lach and Thanh Phu districts of Ben Tre province and Long My town of Hau Giang province. Meanwhile, areas with low salinity sensitivity are Cho Gao district in Tien Giang province and Long Ho district in Vinh Long province.

The results of standardization and weight determination for criteria representing salinity adaptive capacity are presented in Table 5.

The salinity adaptive capacity map was created in the ArcGIS 10.8 environment, Fig. 6.

The results indicate that the areas with the highest salinity adaptive capacity are Go Cong Tay, Thach Phu, and Mo Cay Bac districts in Ben Tre province, Vinh Long city in Vinh Long province.

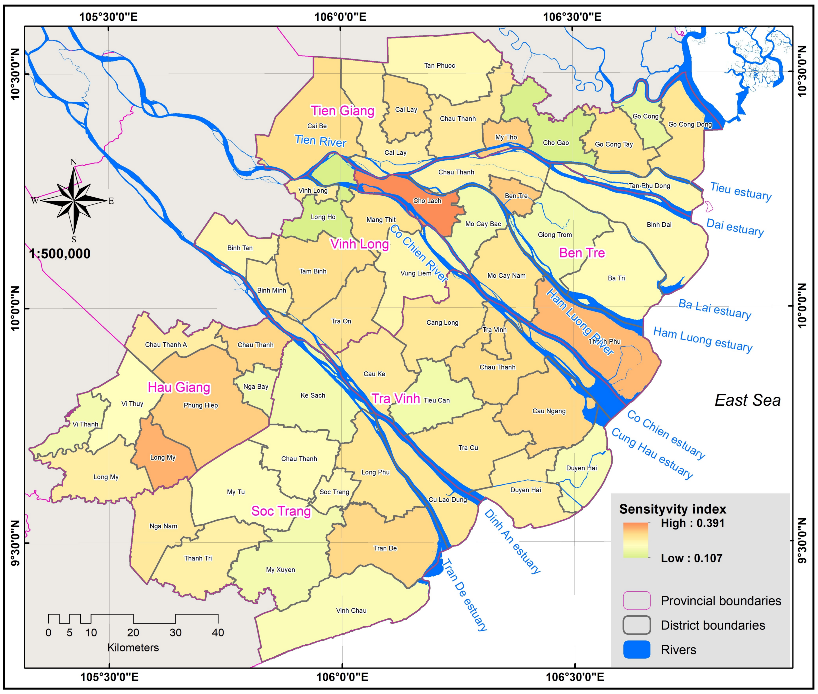

Figure 5. The salinity sensitivity map

Table 5. The normalization and weight determination results of salinity adaptive capacity criteria

Provinces	Districts	Criteria of Adaptive Capacity (AC)									
		AC1	AC2		AC3	AC4		AC5		AC6	
		AC1-1	AC2-1	AC2-2	AC3-1	AC4-1	AC4-2	AC5-1	AC5-2	AC6-1	AC6-2
Ben Tre	Ben Tre	0.71	1.0	0.30	0.3	0.00	0.00	0.69	0.73	0.00	0.00
	Ba Tri	0.43	1.0	0.21	0.3	0.52	0.01	0.77	0.01	0.10	0.00
	Binh Dai	0.48	1.0	0.24	0.4	0.39	0.00	0.62	0.00	0.12	0.00
	Cho Lach	0.33	0.9	0.17	0.2	0.00	0.09	0.27	0.00	0.00	0.00
	Chau Thanh	0.72	1.0	0.06	0.4	0.00	0.02	0.69	0.02	0.00	0.00
	Giong Trom	0.40	0.9	0.16	0.4	0.53	0.01	0.69	0.01	0.00	0.00
	Mo Cay Bac	0.39	0.8	0.14	0.2	0.00	0.00	0.38	0.00	0.00	0.00
	Mo Cay Nam	0.27	0.9	0.26	0.3	0.00	0.01	0.46	0.01	0.00	0.00
	Thanh Phu	0.18	0.9	0.27	0.2	0.57	0.00	0.54	0.01	0.05	0.00
Hau Giang	Chau Thanh	0.56	0.8	0.12	0.4	0.89	0.01	0.12	0.08	0.00	0.18
	Chau Thanh A	0.42	0.9	0.32	0.3	0.99	0.00	0.27	0.06	0.70	0.18
	Long My	0.27	0.8	0.28	0.1	0.99	0.00	0.12	0.04	0.76	0.18
	Long My (town)	0.31	0.0	1.00	0.2	1.00	0.00	0.15	0.10	0.01	0.18
	Nga Bay	0.46	0.6	0.33	0.2	0.91	0.01	0.08	0.10	0.00	0.18
	Phung Hiep	0.36	0.9	0.13	0.0	0.96	0.00	0.38	0.09	1.00	0.18
	Vi Thanh	0.38	0.7	0.38	0.3	0.87	0.01	0.35	0.33	0.36	0.18
	Vi Thuy	0.71	0.4	0.34	0.1	0.96	0.00	0.19	0.07	0.16	0.18
Soc Trang	Chau Thanh	0.21	0.9	0.28	0.5	0.90	0.00	0.12	0.06	0.08	0.16
	Cu Lao Dung	0.36	1.0	0.40	0.1	0.00	0.00	0.12	0.07	0.10	0.16
	Ke Sach	0.32	1.0	0.32	0.1	0.71	0.00	0.31	0.10	0.01	0.16
	Long Phu	0.09	0.9	0.34	0.3	0.75	0.00	0.23	0.09	0.06	0.16
	My Tu	0.00	1.0	0.45	0.2	0.97	0.00	0.19	0.07	0.05	0.16

Provinces	Districts	Criteria of Adaptive Capacity (AC)									
		AC1	AC2		AC3	AC4		AC5		AC6	
		AC1-1	AC2-1	AC2-2	AC3-1	AC4-1	AC4-2	AC5-1	AC5-2	AC6-1	AC6-2
	My Xuyen	0.50	0.9	0.26	0.2	0.86	0.00	0.27	0.07	0.06	0.16
	Nga Nam	0.30	1.0	0.36	0.1	0.99	0.00	0.12	0.08	0.11	0.16
	Soc Trang	0.64	1.0	0.36	0.4	0.72	0.00	0.50	0.70	0.02	0.16
	Thanh Tri	0.02	1.0	0.45	0.2	0.96	0.00	0.19	0.14	0.02	0.16
	Tran De	0.17	0.9	0.32	0.3	0.77	0.00	0.23	0.08	0.12	0.16
	Vinh Chau	0.30	1.0	0.24	0.2	0.63	0.00	0.19	0.12	0.15	0.16
Tien Giang	Cai Be	0.46	0.9	0.12	0.3	0.96	0.01	1.00	0.20	0.02	0.21
	Cai Lay	0.46	0.9	0.09	0.1	0.78	0.02	0.50	0.14	0.10	0.21
	Cai Lay (town)	0.41	1.0	0.24	0.3	0.92	0.01	0.62	0.31	0.01	0.21
	Cho Gao	0.47	1.0	0.18	0.3	0.82	0.02	0.62	0.17	0.08	0.21
	Chau Thanh	0.65	0.9	0.04	0.5	0.95	0.00	0.69	0.28	0.02	0.21
	Go Cong	0.30	0.9	0.23	0.3	0.80	0.00	0.35	0.25	0.10	0.21
	Go Cong Dong	0.34	1.0	0.14	0.3	0.73	0.01	0.27	0.17	0.11	0.21
	Go Cong Tay	0.36	0.9	0.13	0.3	0.84	0.00	0.27	0.16	0.21	0.21
	My Tho	0.74	0.9	0.23	0.4	0.82	1.00	1.00	0.84	0.01	0.21
	Tan Phu Dong	0.31	1.0	0.22	0.2	0.59	0.00	0.00	0.09	0.09	0.21
	Tan Phuoc	0.51	0.8	0.20	1.0	0.88	0.00	0.27	0.13	0.02	0.21
Tra Vinh	Cau Ke	0.18	0.9	0.29	0.3	0.77	0.00	0.19	0.08	0.03	0.37
	Cau Ngang	0.24	0.9	0.33	0.2	0.64	0.00	0.38	0.04	0.05	0.37
	Cang Long	0.33	1.0	0.38	0.1	0.81	0.00	0.31	0.10	0.02	0.37
	Chau Thanh	0.34	0.9	0.23	0.1	0.65	0.00	0.46	0.07	0.03	0.37
	Duyen Hai	0.35	0.8	0.18	0.1	0.51	0.00	0.04	0.03	0.02	0.37
	Duyen Hai (town)	0.70	0.9	0.69	0.7	0.51	0.00	0.08	0.05	0.03	0.37
	Tieu Can	0.45	1.0	0.00	0.3	0.70	0.00	0.19	0.03	0.02	0.37
	Tra Cu	0.24	1.0	0.27	0.2	0.58	0.01	0.42	0.12	0.05	0.37
	Tra Vinh	1.00	0.9	0.36	0.3	0.54	0.01	0.85	0.91	0.00	0.37
Vinh Long	Binh Minh	0.61	0.9	0.22	0.3	0.88	0.05	0.12	0.09	0.00	1.00
	Binh Tan	0.50	1.0	0.23	0.1	0.97	0.04	0.23	0.08	0.05	1.00
	Long Ho	0.57	0.9	0.17	0.3	0.89	0.03	0.50	0.17	0.18	1.00
	Mang Thit	0.31	1.0	0.27	0.2	0.90	0.02	0.27	0.07	0.09	1.00
	Tam Binh	0.42	1.0	0.25	0.1	0.93	0.00	0.46	0.13	0.25	1.00
	Tra On	0.28	1.0	0.45	0.1	0.90	0.01	0.35	0.11	0.27	1.00
	Vinh Long	0.75	0.9	0.34	0.3	0.77	0.01	0.42	1.00	0.01	1.00
	Vung Liem	0.20	0.9	0.32	0.0	0.91	0.01	0.58	0.10	0.42	1.00
	Var	0.038	0.026	0.023	0.025	0.071	0.085	0.018	0.057	0.051	0.038
	$\frac{1}{\sqrt{\text{Var}}}$	5.151	6.185	6.530	6.263	3.745	3.434	7.502	4.204	4.411	5.161
	w_{ij}	0.528	0.486	0.514	1.00	1.00	0.314	0.686	0.488	0.512	0.614

The areas with the lowest salinity adaptive capacity are the Tan Phuoc and Tan Phu Dong districts in Ben Tre province.

The salinity vulnerability map was built in the ArcGIS 10.8 environment by overlaying the salinity sensitivity (Fig. 5) and the salinity adaptive capacity (Fig. 6).

The obtained results demonstrate that the areas with the highest salinity vulnerability are Cho Lach and Tan Phu Dong districts in Ben Tre province. The areas with the lowest salinity vulnerability are the Mo Cay Bac district in Ben Tre province, Cho Gao district in Tien Giang province, and Tieu Can district in Tra Vinh province.

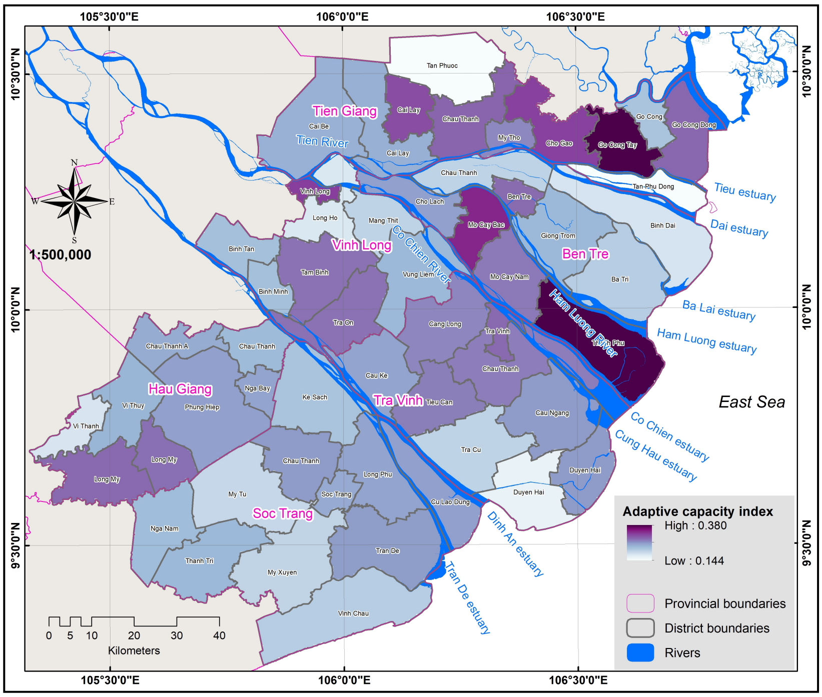

Figure 6. The salinity adaptive capacity map

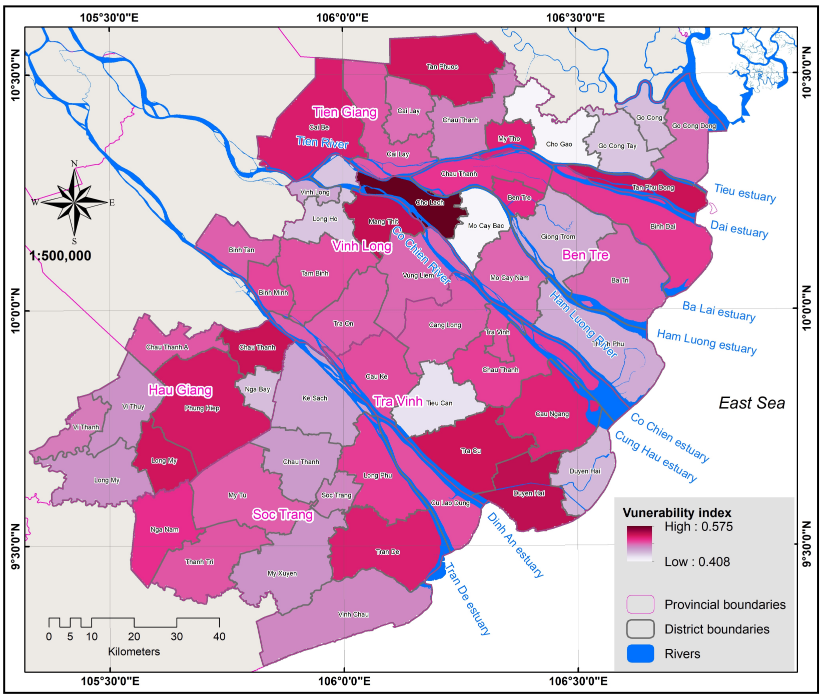

Figure 7. The salinity vulnerability map

3.4. Construction of the salinity risk map

The salinity zoning map was created in the ArcGIS 10.8 environment by overlaying the salinity hazard, exposure, and vulnerability (Fig. 8). The results show that the areas with the highest salinity risk are Ba Tri, Binh Dai and Thanh Phu districts of Ben Tre province and the Tan Phu Dong district of Tien Giang province. The areas with the lowest salinity risk are Vinh Long, Hau Giang, and part of Tien Giang province. The areas with no salinity risk are Vinh Long and Hau Giang provinces (Fig. 9).

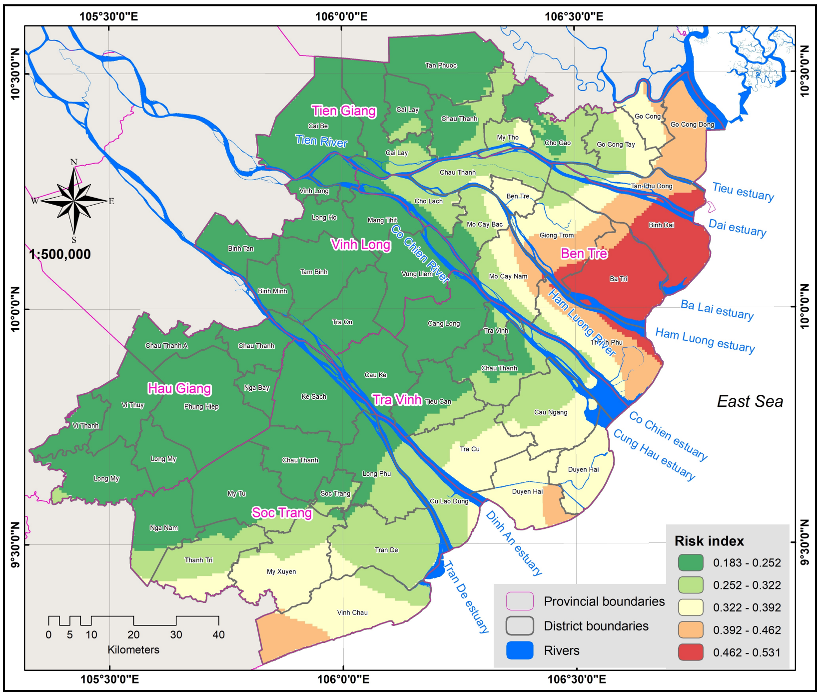

Figure 8. The salinity risk zoning map

Generally, the areas with the high salinity risk are often adjacent directly to the East Sea and have dense rivers and canals. These results are consistent with the recommendations of local authorities and the Standing Office of the National Steering Committee for Natural Disaster Prevention and Control in the 2020 dry season [41].

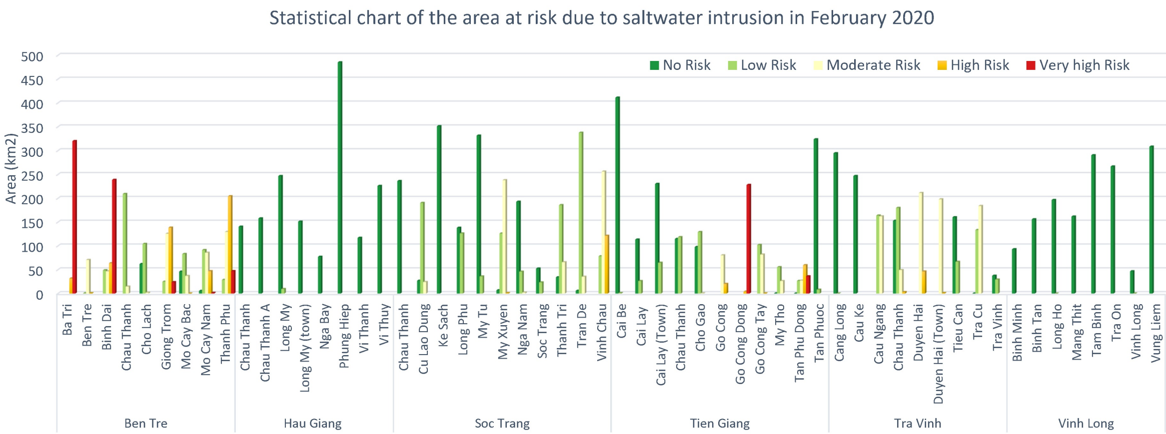

Figure 9. The statistical graph of salinity risk in districts and provinces

4. Conclusions

Salinity intrusion greatly impacts the lives and traditional livelihoods of the local community in the Mekong Delta. This study provided salinity intrusion risk assessment based on the IPCC's framework, a practical, comprehensive approach for the Mekong Delta region, primarily because most people's livelihoods depend on agricultural production. The criteria selected for the salinity risk assessment consist of human, socio-economic, health, education, production, and environmental factors representing the hazard, exposure, and vulnerability components. In addition, interdisciplinary factors such as gender and age groups are used in the salinity risk assessment. The results indicate an overall picture of salinity risk and its impacts on people's livelihoods in the Mekong Delta region. The Ba Tri, Binh Dai, and Thanh Phu districts of Ben Tre province and part of Tan Phu Dong district of Tien Giang province are high-salinity risk areas because these districts are situated near the East Sea and have dense rivers and canals. These results have also been verified by the assessments of the local authorities and the Standing Office of the National Steering Committee for Natural Disaster Prevention and Control in 2020. Generally, the results of this study allow local authorities and communities to proactively respond to salinity intrusion and develop policies to support local communities in a sustainable and long-term way.

The current study assessed the salinity risk based on in-situ data gathered from 68 salinity monitoring stations and 156 salinity prevention culverts across six provinces in the Mekong Delta in 2020. However, this study cannot construct a salinity intrusion forecast map or predict the trend of salinity intrusion in the following years to respond effectively to the issue. We will conduct the salinity intrusion predictive map by updating the in-situ datasets and using advanced machine learning algorithms in the future.

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