

Vulnerability assessment of coastal wetlands in Minjiang River Estuary based on cloud model under sea level rise

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Abstract

The change of coastal wetland vulnerability affects the ecological environment and the economic development of the estuary area. In the past, most of the assessment studies on the vulnerability of coastal ecosystems stayed in static qualitative research, lacking predictability, and the qualitative and quantitative relationship was not objective enough. In this study, the “Source-Pathway-Receptor-Consequence” model and the Intergovernmental Panel on Climate Change vulnerability definition were used to analyze the main impact of sea level rise caused by climate change on coastal wetland ecosystem in Minjiang River Estuary. The results show that: (1) With the increase of time and carbon emission, the area of high vulnerability and the higher vulnerability increased continuously, and the area of low vulnerability and the lower vulnerability decreased. (2) The eastern and northeastern part of the Culu Island in the Minjiang River Estuary of Fujian Province and the eastern coastal wetland of Meihua Town in Changle District are areas with high vulnerability risk. The area of high vulnerability area of coastal wetland under high emission scenario is wider than that under low emission scenario. (3) Under different sea level rise scenarios, elevation has the greatest impact on the vulnerability of coastal wetlands, and slope has less impact. The impact of sea level rise caused by climate change on the coastal wetland ecosystem in the Minjiang River Estuary is mainly manifested in the sea level rise, which changes the habitat elevation and daily flooding time of coastal wetlands, and then affects the survival and distribution of coastal wetland ecosystems.

Key words: vulnerability assessment, cloud model, coastal wetland, Minjiang River Estuary

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1 Introduction

The coastal wetland is a transitional zone between terrestrial ecosystem and marine ecosystem. It plays an important role in regulating flood storage, promoting siltation and land reclamation, degrading pollutants, protecting biodiversity and providing production and living resources for human beings. It is a key area of interaction between land and sea (Wu et al., 2008). According to the sixth the Intergovernmental Panel on Climate Change (IPCC) assessment report (AR6), the most significant change in global climate in the past 100 years is the intensification of global warming (Zhou and Qian, 2021). The rise in sea temperature caused by climate warming and the melting of large-scale ice and snow directly lead to global sea level rise. However, the coastal wetlands are extremely sensitive to sea level rise caused by global extreme climate. Sea level rise may lead to a sharp decline in coastal wetland area, habitat degradation and biodiversity decline (Osland et al., 2022). Due to the interference of global climate change and sea level rise, the coastal wetland environment in estuaries is facing great challenges. Therefore, to strengthen the research of estuary coastal wetland, not only for regional ecological environment security and social and economic develop-

ment has an important reference, but also for deepening the understanding of land-sea interaction is of great significance, for many years by academia and government attention.

Since the 1970s, global change has become the focus of many scholars' attention and research. Climate change is an important part of global change research (Wang et al., 2012). The study of coastal wetland vulnerability under the background of sea level rise began in the late 1980s (Chu et al., 2005). Since the first IPCC assessment report in 1990, many scholars at home and abroad have carried out research on the vulnerability assessment of coastal ecosystem under the influence of climate change. The concept of vulnerability index and risk level was first proposed by Gornitz in 1991 (Gornitz, 1991), and has been widely used in vulnerability assessment of the Pacific and Atlantic coasts of the United States. The distributed process model proposed by Bryan et al. (2001) selected four indicators of orientation, elevation, morphology and slope to evaluate the vulnerability of coastal zones under the influence of sea level rise. Based on cloud theory, Zhu et al. (2019) selected coastal morphology, coastal elevation, coastal slope, coastal buffer capacity, effective wave height, road value and building value as indicators to construct a coastal

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vulnerability assessment index system for Xiamen Island, and used cloud model assessment methods to quantitatively measure the spatial differentiation characteristics of coastal vulnerability in Xiamen Island. Chinese scholars have also carried out assessments of ecosystem vulnerability in large watershed areas such as the Huanghe River Estuary, the Changjiang River Estuary and the Zhujiang River Estuary (Wang et al., 2012).

Based on the above analysis, there are few studies on the impact of climate change on coastal wetlands in China, most of which remain at the qualitative assessment level of large watersheds, and there is still a lack of vulnerability assessment of the impact of process-based climate change on coastal wetlands in small watersheds. In addition, previous studies have not paid enough attention to the vulnerability of coastal wetlands in the Minjiang River Estuary, and the qualitative assessment lacks predictability (Cui et al., 2016). In this paper, the vulnerability assessment system and method of coastal wetlands under the influence of climate change are constructed to objectively and quantitatively evaluate the vulnerability of coastal wetland ecosystems under the influence of climate change. A vulnerability assessment index system based on sea level rise rate, erosion rate, habitat elevation, average daily flooding time of plants, tidal flat slope, deposition rate and vegetation coverage is constructed. Each vulnerability index is quantified on the ArcGIS platform, and the vulnerability index is calculated and graded. The quantitative spatial assessment method of coastal wetland ecosystem vulnerability under the influence of sea level rise was established. The cloud model was used to predict and evaluate the spatial differentiation characteristics of coastal wetland vulnerability in Minjiang River Estuary. This paper attempts to explore the vulnerability distribution of coastal wetlands in Minjiang River Estuary in different scenarios in the future, analyze the internal dynamic factors and provide scientific basis for formulating practical coping strategies and measures.

2 Study area

The Minjiang River is the largest river flowing into the East China Sea in Fujian Province. Minjiang River originated in Jianning County Junkou Town, which is the junction of Fujian and Jiangxi provinces. The three tributaries of Jianxi River, Shaxi River and Futun River converge near the Yanping District of Nanping City to form a total flow, called Minjiang River. The Minjiang River Estuary is located at 25°50′43″N to 26°09′42″N and

119°36′35″E to 119°41′05″E (Fig. 1). From the dynamic conditions, the Minjiang River Estuary is a strong tidal estuary, which is a regular semi-diurnal tide. The waves are mainly wind waves, followed by swells. The area belongs to the transitional area of mid-subtropical monsoon climate and south subtropical marine monsoon climate. The annual average temperature is 19.7°C.

The coastal wetland of Minjiang River Estuary covers an area of 4 130.19 m², with an average elevation of −0.698 m and an average slope of 0.58° (He et al., 2018). Different floras are distributed zonally in the study area and gradually evolve to terrestrial plant communities from the low tide zone to the supra tidal zone. The *Spartina alterniflora* community is distributed at the outermost edge of the inter tidal zone. The middle tidal zone is mainly composed of *Phragmites australis*, and gradually transitions to the short-leaf river malaccensis and other groups in the high tidal zone.

3 Methods

3.1 Definition of vulnerability

The vulnerability was first used in the field of disaster risk research in geography, and has been widely used in land use, vegetation cover change, ecological environment assessment, climate change and other research (Wang et al., 2012). The IPCC assessment report points out that vulnerability refers to the degree of damage or harm of climate change to natural or social systems, and is a function of the characteristics, magnitude and rate of change of climate change in the system and its sensitivity and adaptability (Intergovernmental Panel on Climate Change, 2001). The relationship between system vulnerability (V) and system exposure (E), sensitivity (S) and fitness (A) can be expressed as

$$V = E + S - A. \quad (1)$$

3.2 Vulnerability assessment model

In the study of coastal zone vulnerability assessment, the IPCC general method is used to evaluate the vulnerability of the coastal zone. This method has a standardized process and unified operation steps, but ignores the spatial distribution of sea level rise, and the index system covers a wide range, and the influence degree dimension is difficult to unify. There are also variables to choose a simple Coastal Vulnerability Index model, there are regional differences, making the results relative, different re-

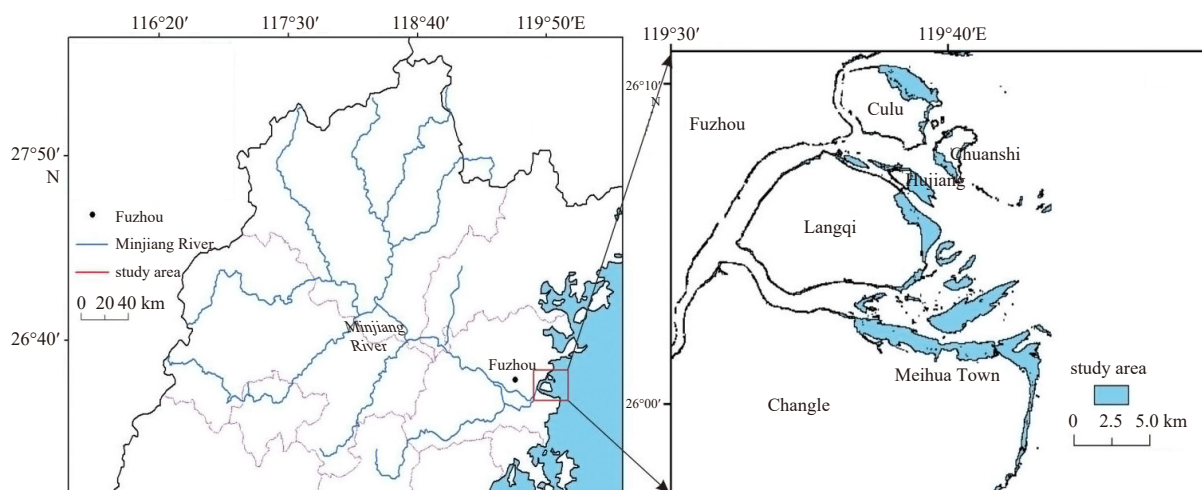


Fig. 1. Study area.

gions are difficult to compare. At present, the “pressure-state-response (PSR)” model is widely used (Wang et al., 2012). The PSR model has a relatively obvious causal relationship. The evaluation index system is constructed from the mechanism of index generation, but this model has many indicators and the relationship is difficult to be completely clear. Based on the PSR model, the EU first proposed the “Source-Pathway-Receptor-Consequence (SPRC)” model in a project to study and assess the impact of sea level rise and storm surge caused by climate change on the socioeconomic and ecological environment of the coastal zone (Li et al., 2014). The SPRC evaluation model is based on causality and can reflect the interaction and process that affect the “Source” and “Receptor”. In this study, the SPRC model was used to construct the vulnerability assessment model of coastal wetland in Minjiang River Estuary based on a cloud model under the background of sea level rise from three aspects of exposure, sensitivity and adaptability of system vulnerability (Fig. 2).

The coastal wetland is distributed in the water body and its inter tidal zone within 5 m water depth at low tide. Its elevation and sediment erosion rate directly affect the survival and distribution of the coastal wetland ecosystem, so it is very sensitive to the sea level rise caused by climate change. In the SPRC assessment model applied in this study, sea level rise due to climate change is a potential source of impact on coastal wetland ecosystems (S). Inter tidal sediment deposition and seawater erosion can accelerate the impact of sea level rise on coastal wetlands, while a small intertidal slope can alleviate or offset the impact of sea level rise to a certain extent. The dynamic balance of sediment erosion and deposition in the inter tidal zone brought by rivers and the open sea is also an important factor affecting the relative sea level rise. Absolute sea level rise affects the habitat changes of different coastal wetland receptors (R) through the coastal sedimentary erosion rate pathway (P). Under the dynamic conditions of absolute sea level rise and coastal wetland erosion, the relative sea level change may change the elevation of coastal wetland and affect the coastal wetland ecosystem. When the relative sea level rise rate exceeds the tolerance range of coastal wetland ecosystems, it will lead to a change of ecosystem structure and eventually lead to the destruction of the biological environment.

3.3 Vulnerability assessment index system

Based on the definition of vulnerability by IPCC and the analysis of the SPRC assessment model, this study constructed the vulnerability assessment index system of the coastal wetland ecosystem in Minjiang River Estuary under the background of sea level rise from three aspects: exposure, sensitivity and adaptability (Table 1). The impact of climate change on the coastal wetland system in the Minjiang River Estuary is mainly due to the interaction between sea level rise and erosion deposition rate. Whether the coastal wetland ecosystem can adapt to the changes of inter tidal zone elevation and flooding time. The selected indicators can qualitatively and quantitatively reflect the impact of sea level rise on coastal wetland ecosystems, and the duplication of indicators should be avoided. At the same time, the indicators should have the characteristics of quantifiable and data availability, and their data have spatial and temporal heterogeneity.

The data sources of the wetland vulnerability assessment index system in Minjiang River Estuary are wide, among which the annual storm surge frequency and sea level rise rate are derived from Fujian Marine Disaster Announcement (gi.mnr.gov.cn/202205/PO20220507388929214813.pdf) and China Sea Level Announcement (gi.mnr.gov.cn/202205/t20220507_2735509.html). The erosion rate and deposition rate of the beach are derived from the data of the Naval Hydrographic Survey Bureau of the Chinese People's Liberation Army (hydro.ngd.gov.cn/Default.aspx). Tidal flat slope and habitat elevation are extracted from the original DEM of the geospatial data cloud (www.gscloud.cn/search). The average daily flooding time are derived from the tidal table of Minjiang River Estuary in Fujian Province and the elevation data of the Minjiang River Estuary wetland. The original data of vegetation coverage are derived from Landsat 8 OLI_TIRS satellite digital products of geospatial data cloud, processed by ENVI and GIS platforms. Including radiation calibration, atmospheric correction, calculation of normalized vegetation index inversion. And the date is September 20, 2021.

3.4 Vulnerability evaluation index weight calculation

There are different methods for the weight division of coastal wetland vulnerability assessment indicators, such as the analytic

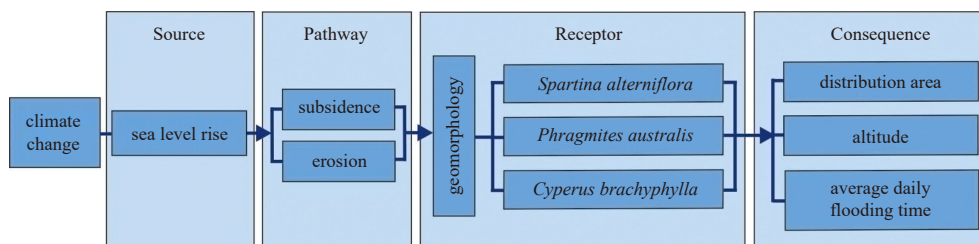


Fig. 2. Evaluation pattern diagram.

Table 1. Vulnerability assessment index of coastal wetland in the Minjiang River Estuary

Classification of assessment	Goal layer	Indicator layer	Label
Exposure	natural stress	annual number of storm surges/a ⁻¹	A1
	natural stress	rising rate of sea level/(mm·a ⁻¹)	A2
	natural stress	corrosion rate/(cm·a ⁻¹)	A3
Sensitivity		slope of tidal flat/(°)	C1
		daily average flooding time/(h·d ⁻¹)	C2
		elevation/m	C3
Adaptability	community response	vegetation coverage	D1
	catural response	rate of sedimentation/(cm·a ⁻¹)	D2

hierarchy process, expert scoring method, resilience scorecard method, model method and tool set (Li et al., 2022). Different methods have their own advantages and disadvantages. Because the cloud model itself has the advantages of fuzzy theory and probability theory, and the cloud model has been able to show the uncertainty and fuzziness of qualitative concepts. It can effectively avoid the absoluteness and subjectivity of evaluation and judgment. And it is suitable for the study of coastal wetland ecological vulnerability with complexity and uncertainty (Shen, 2018). Therefore, in order to avoid the existence of subjective factors in the process of weight assignment, this study adopts the equal weight method (Zhu et al., 2019) to assign the weight of vulnerability assessment.

3.5 Cloud model evaluation

3.5.1 Cloud model concept

The cloud model was first proposed by Deyi Li, an academician of the Chinese Academy of Engineering, in 1995 (Wu, 2014). It is an uncertain transformation model for dealing with qualitative concepts and quantitative descriptions. Has been successfully applied to natural language processing, data mining, decision analysis, intelligent control, image processing and other fields. The model effectively reduces the randomness and uncertainty in the assessment, and makes the assessment results more scientific and real. The cloud model uses three digital features of expectation E_x , entropy E_n and hyper entropy H_e to represent a concept as a whole.

Numerical feature expectation E_x of cloud model: the expectation of spatial distribution of cloud droplets in a universe of discourse. Generally speaking, it is the point that can best represent the qualitative concept, or the most typical sample of this concept quantification.

Entropy E_n : Uncertainty measure of qualitative concept, determined by randomness and fuzziness of concept. On the one hand, E_n is a measure of the randomness of a qualitative concept, reflecting the degree of dispersion of cloud droplets that can represent the qualitative concept; on the other hand, it is also a measure of the qualitative concept, which reflects the range of values of cloud droplets that can be accepted by the concept in the domain space.

Hyper entropy H_e : is the uncertainty measure of entropy, namely the entropy of entropy. It is determined by the randomness and fuzziness of entropy.

Suppose that N is a quantitative domain and R is the qualitative concept corresponding to the quantitative domain N . If the quantitative value $x \in N$ and x is a random realization of the qualitative concept R , x satisfies the degree of certainty for R ,

$$\mu(x) = \exp \left[\frac{(x_i - E_x)^2}{2(E'_n)^2} \right], \quad (2)$$

where i denotes a random number, take 1, 2, 3, ..., n ; E'_n represents the standard deviation of the random array. Then the distri-

bution of x on the domain N is a normal cloud distribution. x is the quantitative data as well as a cloud droplet, and the model formed by several cloud droplets reflects the transformation from qualitative concept to quantitative value.

3.5.2 Cloud model algorithm steps

The cloud model generation algorithm steps are as follows:

- (1) Produce a normal random number x_i with the expected value E_x and the variance E_n ;
- (2) Generate a normal random number E_x with the expected value E_n and variance H_e ;
- (3) Calculate y_i according to Eq. (2);
- (4) Let (x_i, y_i) be a cloud droplet, which is a concrete realization of the number of linguistic values represented by the cloud, where x is the numerical value corresponding to this time of the qualitative concept in the universe of discourse, and y_i is a measure of the degree to which this linguistic value belongs;
- (5) Use Python to repeat steps (1) to (4) until the number of cloud droplets that meet the requirements is generated.
- (6) Determine the evaluation results. According to the principle of maximum membership degree, the grade corresponding to the maximum membership degree of evaluation factors is selected as the evaluation result.

3.6 Vulnerability evaluation criteria of each index

Based on the natural discontinuity method in ArcGIS and related research results (Li et al., 2014), combined with the classification criteria of wetland vulnerability, the five coastal wetland vulnerability impact indicators in this study were graded. After fine-tuning individual intervals according to the degree of dispersion of cloud droplets obtained by the cloud model, the grading interval division results of each indicator evaluation standard are shown in Table 2.

4 Results

The sixth assessment report of IPCC pointed out that the current rate of sea level rise is accelerating and will continue to rise in the future. In the context of sea level rise, this study selected sea level rise heights (Table 3) at three different time scales and different emissions to predict the vulnerability of coastal wetlands in the Minjiang River Estuary under different scenarios in different time series in the future. The data in the table are from the IPCC Sixth Assessment Report (Zhang et al., 2022).

4.1 Index membership degree

In this study, cloud model parameters (Table A1) combined with fuzzy variable theory relative difference degree theory. Adjusting the determination of the boundary value of the proximity index to the adjacent level (Gao et al., 2018) and determining the positive cloud parameters (Zhou et al., 2014; Tian, 2018). Firstly, the factor set domain and comment set domain of evaluation object are established. Secondly, determine the weight set (this article uses equal weight). Fuzzy matrix is established and membership degree of evaluation factors is calculated by normal cloud

Table 2. Vulnerability evaluation interval division of each index

Index	Micro-degree	Slight	Moderate	Gravity	Utmost
Elevation/m	(3.16, 4.7]	(1.62, 3.16]	(0.08, 1.62]	(−1.46, 0.08]	[−3, −1.46]
Daily average flooding time/(h·d ^{−1})	(20, 24]	(15, 20]	(10, 15]	(5, 10]	[0, 5]
Slope of tidal flat/(°)	[0, 1]	(1, 3]	(3, 5]	(5, 7]	(7, 13]
Vegetation coverage	(0.8, 1]	(0.6, 0.8]	(0.4, 0.6]	(0.2, 0.4]	[0, 0.2]
Sedimentation erosion rate/(cm·a ^{−1})	(0.23, 0.59]	(−0.12, 0.23]	(−0.4, −0.12]	(−1, −0.4]	[−2.29, −1]

Table 3. Sea level rise table under different time series scenarios

Time-scale	Scenario	Sea level rise height/m	Value-taking/m
Short time-scale (2020–2050)	low emission scenarios (SSP1-1.9)	0.15–0.23	0.23
	high emission scenarios (SSP5-8.5)	0.20–0.30	0.30
Mid time-scale (2020–2100)	low emission scenarios (SSP1-1.90)	0.28–0.55	0.55
	high emission scenarios (SSP5-8.5)	0.63–1.21	1.21
Long time-scale (2020–2150)	low emission scenarios (SSP1-2.6)	0.5–1.0	1.00
	high emission scenarios (SSP5-8.5)	1.0–1.9	1.90

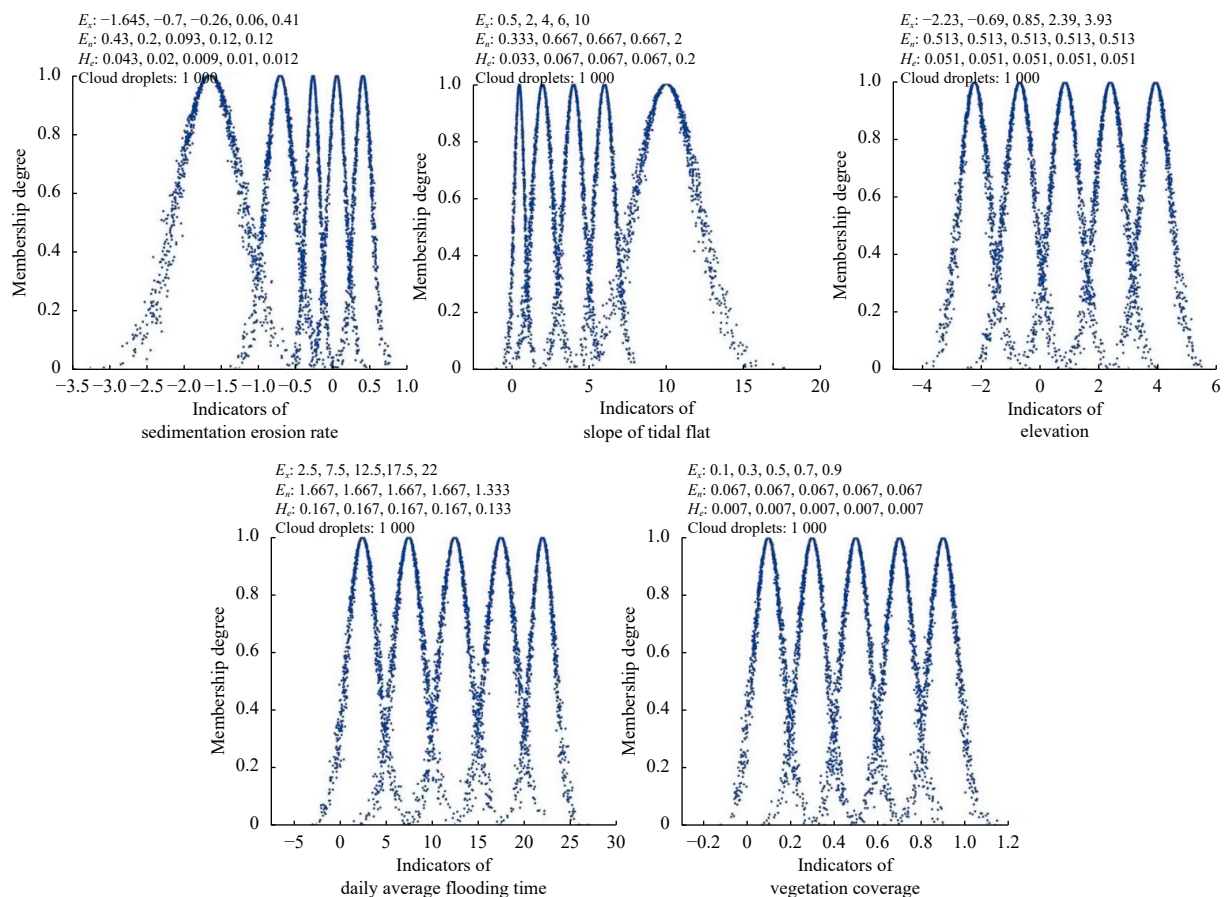
model. The super entropy coefficient reflects the aggregation degree of cloud droplets. The value of super entropy is proportional to the thickness of the cloud. The greater the value of super entropy, the thicker the cloud. Finally, according to the parameters under different scenarios, the forward cloud generator is used to determine the cloud model membership matrix of the corresponding level of each index. Repeatedly run multiple forward cloud generators to increase the credibility of the values, taking the combined average as the evaluation value (Hou, 2016).

According to the principle of maximum membership degree (Zhu et al., 2019), the vulnerability index of coastal wetland in the Minjiang River Estuary area was evaluated by a cloud model. The membership degree of each index was different under different vulnerability degrees, and the maximum membership degree was selected. Comprehensive Fig. 3 (Figs A1–A6) shows that the entropy value E_n is less than 2, the value is small, indicating that the uncertainty of the evaluation results is low; the hyper entropy H_e does not exceed 0.2, indicating that the stability of the evaluation results is high. According to the 3E principle of the cloud

model (Huo et al., 2022), the evaluation results are more reliable when $E_n/3 > H_e$. Based on the above, the cloud model works better.

4.2 Various indexes

In this study, the erosion rate under natural stress, vegetation coverage under social response, deposition rate under natural response, tidal flat slope, habitat elevation and average daily flooding time of plants were constructed from three aspects of exposure, sensitivity and adaptability. By analyzing the indicators under the original scenario (2021 data), it can be concluded that the habitat elevation (Fig. 4a) in the study area shows high in the southwest, low in the northeast, and gradually increasing to the land side. The wetland between Meihua Town and the southeast coast of Langqi Island is lower than the average elevation; The slope of the tidal flat (Fig. 4b) tends to be gentle in the region, ranging from 0 to 0.4, all less than 1; the sediment erosion rate (Fig. 4c) showed a trend of siltation in the north of Culu Island, the southeast of Hujiang Island and the east of Meihua Town in Changle District, among which the siltation in the southeast of

**Fig. 3.** Original cloud diagram.

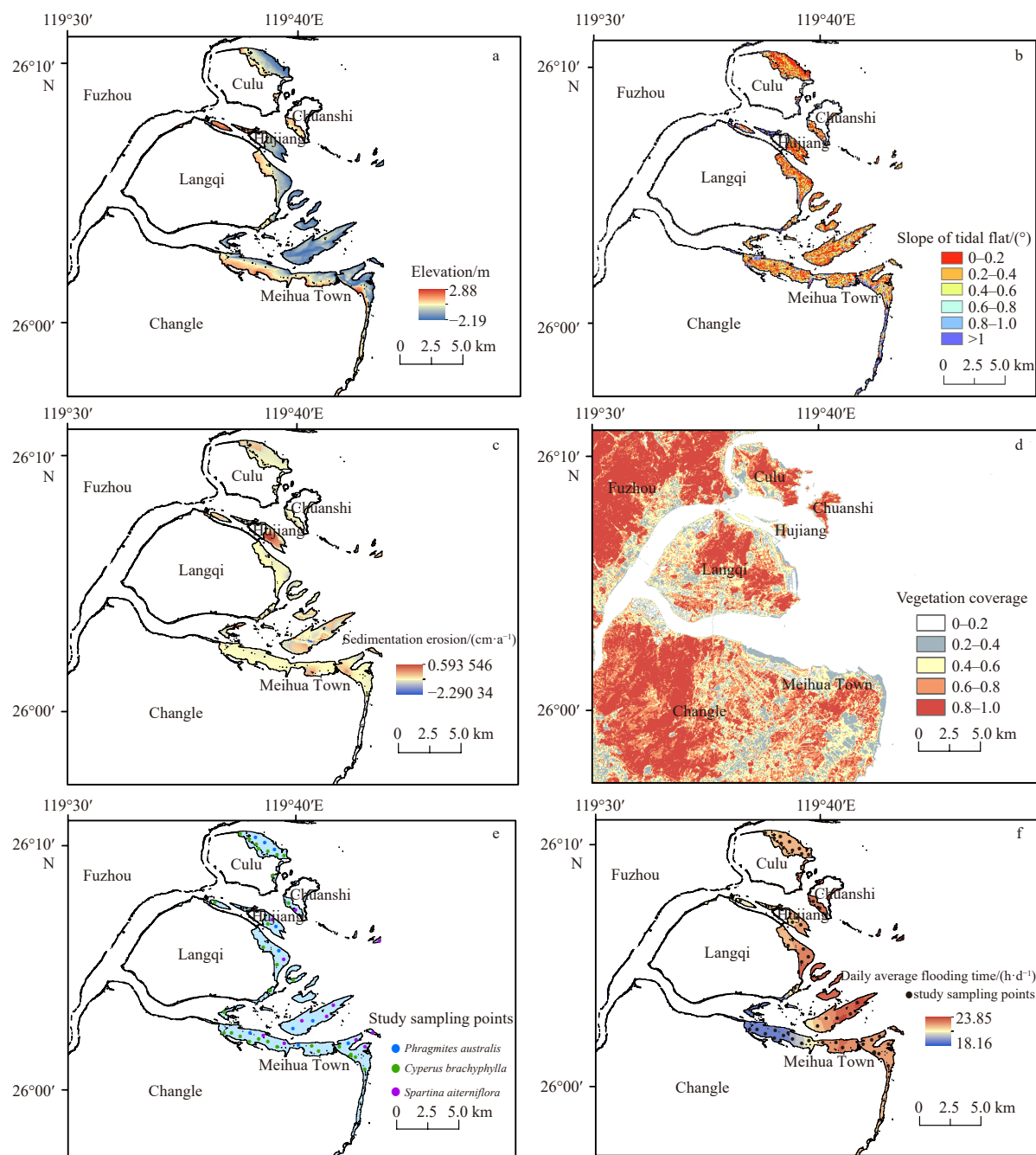


Fig. 4. Original data index diagram: maps of elevation (a); slop of tidal flat (b); sedimentation erosion (c); vegetation coverage (d); study sampling points (e); and daily average flooding time (f).

Hujiang Island was the most significant. There was a trend of sediment erosion in the eastern and southeastern parts of Langqi Island, the central and southern parts of the island between Langqi Island and Meihua Town in Changle District, and the northeastern part of Meihua Town, and the erosion in the southeastern part of Langqi Island was the most obvious. The rest of the study area showed a dynamic equilibrium state of non-erosion and non-deposition. Under the action of sediment deposition erosion, it offsets the possible impact of sea level rise on the coastal wetland habitat in the Minjiang River Estuary. Vegetation coverage (Fig. 4d) showed an increasing trend from west to east in the study area of Langqi Island, and a decreasing trend from north to south in the study area of Changle District. Vegetation coverage generally decreased to the sea side and increased

to the land side. In this study, three species of *Spartina alterniflora*, *Phragmites australis* and *Cyperus brachyphylla* were selected to represent some floras of coastal wetland in the Minjiang River Estuary. Based on previous studies (Liu, 2008; Mi, 2019; Feng, 2020), the research location points of three plants were set up in this paper (Fig. 4e). According to the plant height, habitat elevation of different wetland plants and the tide of the Minjiang River Estuary, the daily average flooding time distribution of plants was simulated by the Kriging interpolation method (Fig. 4f).

4.3 Spatial assessment of vulnerability of coastal wetlands in Minjiang River Estuary under sea level rise

The spatial quantitative evaluation index is the basis of spatial vulnerability assessment. The evaluation index of the coastal

wetland in Minjiang River Estuary is used as a data carrier on the ArcGIS platform. The selected habitat elevation, tidal flat slope, vegetation coverage, average daily flooding time of plants and sediment erosion rate evaluation indicators all have spatial geographical characteristics. The predicted membership degree of each vector point index obtained from the above data through the cloud model is obtained. The membership degree corresponding to the actual value is obtained by the TREND function, and the actual membership degree is multiplied by the weight to accumulate the vulnerability of the vector points in different situations. Finally, through the ArcGIS platform, the vector data is converted into raster data, and the vulnerability index data and evaluation unit are integrated to realize the assignment of spatial evaluation unit. The vulnerability index database of the spatial data and attribute data is established to realize the geospatial quantification of habitat elevation, tidal flat slope, vegetation coverage, daily average flooding time of plants and deposition erosion rate index. The vulnerability distribution of coastal wetland in Minjiang River Estuary under different scenarios is obtained, and the proportion of vulnerability degree of coastal wetland under each scenario is obtained (Table 4). According to the classification of a vulnerability index, the spatial distribution map of coastal wetland vulnerability assessment in Minjiang River Estuary was output under different sea level rise scenarios and different time scales (short time series 2030, medium time series 2050 and long time series 2100).

4.3.1 Vulnerability assessment of coastal wetland in original scenario

In the original scenario (2021 data), the vulnerability distribution of the study area was obtained by using the equal weight method from the above index data in the original scenario (Fig. 5). The area of coastal wetland with low vulnerability accounts for 3.98% in Minjiang River Estuary, while the lower vulnerability and medium vulnerability are 15.30% and 27.65%, respectively (Table 4). The wetlands with low vulnerability and the lower vulnerability are mainly distributed in the eastern and northwestern

parts of Meihua Town, Changle District, and the low vulnerability area is most significant in the eastern part of Meihua Town. The high vulnerability area and the higher vulnerability area account for 20.95% and 32.12%, respectively. The high vulnerability area not only appears in the central section of Meihua Town in the Changle District, but also includes most of the eastern part of Culu Island and the southern part of Chuanshi Island.

4.3.2 Vulnerability assessment of coastal wetlands under different scenarios in short time series

In the past 30 years, under the low emission scenario of sea level rise in Minjiang River Estuary (SSP1-1.9: 0.23 m), the area of low vulnerability and the lower vulnerability in the study area accounted for 1.98% and 14.13%, respectively (Table 4). At this time, the coastal wetland with low vulnerability is mainly distributed in the west bank of Meihua Town, Changle District (Fig. 6a), while the wetland in the east and northeast of Culu Island and a small part of the east of Meihua Town is in high vulnerability. Under the high emission scenario (SSP5-8.5: 0.30 m), the proportion of low vulnerability area in the study area is 1.27%, and the proportion of lower vulnerability area is 13.69% (Table 4). In 2050, the absolute sea level rise exceeded the sediment deposition caused by sedimentation, resulting in an increase in the average daily flooding time of the habitats of the coastal wetlands in the Minjiang River Estuary. The average daily flooding time exceeded the normal survival flooding time of the plants, causing an increase in the vulnerability of coastal wetlands in some areas. Compared with the low emission scenario, the area of high vulnerability areas has a significant increasing trend, mainly distributed in the eastern and northeastern parts of Culu Island, the eastern part of Meihua Town, and some wetlands between Culu Island and Langqi Island (Fig. 6b).

The results of the short time series projection indicate that the sea level rise will have an impact on the coastal wetlands in study area. The wetland in some higher elevation areas and the area between Langqi Island and Culu Island with relatively high deposition rate showed lower vulnerability.

Table 4. Vulnerability proportion table under different scenarios

	Original data	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Low vulnerability	3.98%	1.98%	1.27%	2.78%	2.29%	1.77%	1.98%
Lower vulnerability	15.30%	14.13%	13.69%	12.50%	11.35%	11.90%	10.89%
Medium vulnerability	27.65%	27.53%	26.87%	26.90%	25.40%	26.46%	24.69%
Higher vulnerability	32.12%	33.44%	34.64%	34.80%	35.83%	36.58%	36.78%
High vulnerability	20.95%	22.92%	23.53%	23.02%	25.13%	23.29%	25.66%

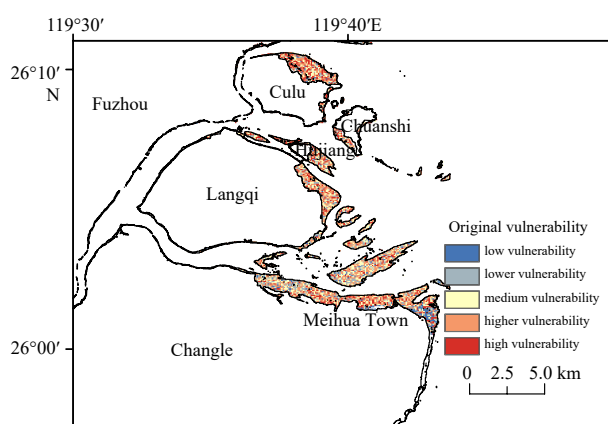


Fig. 5. Original vulnerability result graph.

4.3.3 Vulnerability assessment of coastal wetlands under different scenarios in medium time series

In the past 80 years, under the low emission scenario of sea level rise in Minjiang River Estuary (SSP1-1.9: 0.55 m), the area of low vulnerability and the lower vulnerability in the study area accounted for 2.78% and 12.5%, respectively, and the area of high vulnerability wetland accounted for 23.02% (Table 4). At this time, the coastal wetlands in low vulnerability are mainly distributed in a small part of the western part of Meihua Town, Changle District (Fig. 6c), while the wetlands in the eastern and northeastern part of Culu Island and the eastern part of Meihua Town are in high vulnerability, and the eastern part of Culu Island is the most obvious. Under the high emission scenario (SSP5-8.5: 1.21 m), the area of low vulnerability in the study area accounts for 2.29%, and the area of lower vulnerability accounts for 11.35% (Table 4). Compared with the low emission scenario, the area of low vulnerability is decreasing, and the area of high vulnerability is in-

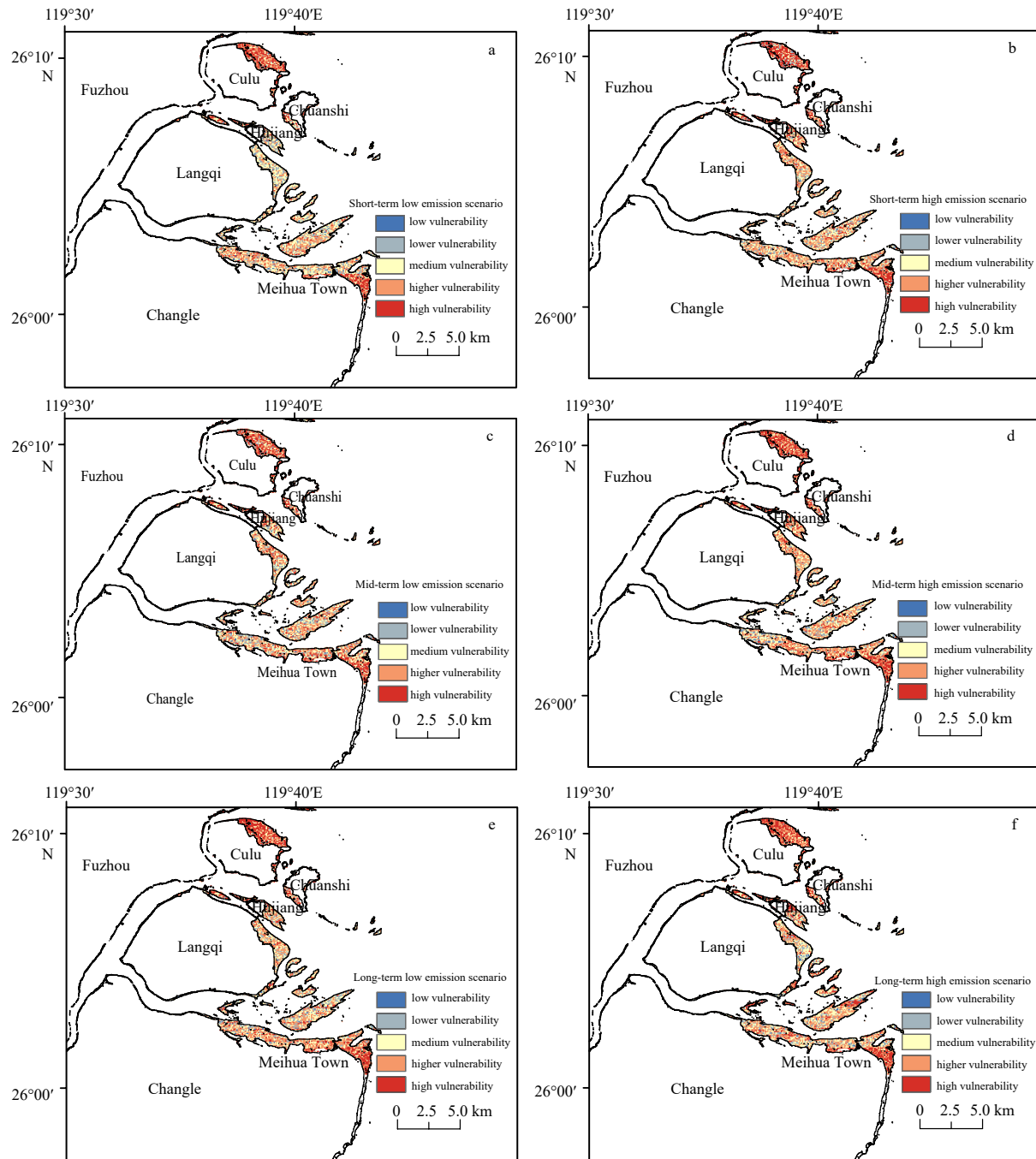


Fig. 6. Vulnerability distribution graph under different scenarios: Scenario 1 (a); Scenario 2 (b); Scenario 3 (c); Scenario 4 (d); Scenario 5 (e); Scenario 6 (f).

creasing to 25.13%. It can be seen that the area of high vulnerability area under the influence of sea level rise shows an increasing trend.

The results of the medium time series projection indicate that the sea level rise will have a considerable impact on the coastal wetland. Under the high emission scenario of 1.21 m absolute sea level rise in 2100, the vulnerability of coastal wetlands in some areas increased significantly. The affected areas mainly occur at the eastern and northeastern parts of Culu Island, the eastern part of Meihua Town, some wetlands between Culu Island and Langqi Island, and the northern part of the eastern part of Langqi Island (Fig. 6d).

4.3.4 Vulnerability assessment of coastal wetlands under different scenarios in long time series

Under the long-term (2020–2150) low-emission scenario (SSP1-2.6: 1 m), the total area of the study area in the low vulnerability and the lower vulnerability areas accounted for 13.67%, and the total area of coastal wetlands in the high vulnerability and the higher vulnerability areas accounted for 59.87% (Table 4). At this time, the coastal wetlands with low vulnerability are distributed in a small part of the coastal wetlands between Meihua Town and Langqi Island in Changle District (Fig. 6e), while the wetlands in the eastern and northeastern parts of Culu Island and most of the eastern part of Meihua Town are still highly vulnerable, and spread to the southern part of Chuanshi Island and

the central part of Meihua Town, especially in the eastern part of Culu Island. Under the high emission scenario (SSP5-8.5: 1.9 m), the proportion of low vulnerability area in the study area is only 1.98%, and the proportion of lower vulnerability area decreased to 10.89% (Table 4). Compared with the low emission scenario, the area of low vulnerability is decreasing, while the area of high vulnerability and higher vulnerability is as high as 62.44%. Under the high emission scenario in 2150, the areas with significant increase of coastal wetland vulnerability are mainly distributed in the east of Meihua Town, the wetland between Culu Island and Langqi Island, the northeast of coastal wetland between Langqi Island and Meihua Town, and the south-east of Langqi Island (Fig. 6f).

The results of the long time series projection indicate that the sea level rise will have a profound impact on the coastal wetland, especially under the SSP5-8.5 scenario (Fig. 6f). Accumulated sea level rise, coupled with relatively low deposition rate and original elevation will cause some lowlands to be submerged. The sea level height exceeds the plant flooding height, which reduces the vegetation coverage. Vulnerability of regional coastal wetlands are increasing.

In summary, the impact of sea level rise caused by climate change on the ecosystem of coastal wetland in Minjiang River Estuary is mainly manifested in that sea level rise changes the habitat elevation and daily average flooding time of coastal wetland, thus affecting the survival and distribution of coastal wetland ecosystem. Finally, the proportion of high vulnerability area of coastal wetland in estuary increased. Thus it affects the survival and distribution of coastal wetland ecosystem (Li et al., 2014; Cui et al., 2016).

5 Discussion

Sea level rise caused by global climate change will have a significant impact on coastal wetlands. The IPCC CZMS report in the early 1990s listed coastal vulnerability assessment as a major issue for the first time (Wang et al., 2012). The study predicts that by 2080, global sea level rise will cause 22% of the world's wetland losses. If combined with the impact of other human activi-

ties, global wetland losses will reach 70%. If there is no corresponding response, global sea level rise will have a serious negative effect. It is the development direction of a coastal wetland vulnerability assessment at present and in the future to construct coastal wetland vulnerability assessment model based on climate change and strengthen quantitative vulnerability assessment (Narayan et al., 2012).

In this study, the SPRC assessment model and the cloud model were used to construct the vulnerability assessment model of coastal wetland in Minjiang River Estuary under the influence of sea level rise based on cloud model. The assessment model provides a way for the establishment of a vulnerability assessment index system and qualitative and quantitative spatial evaluation of the coastal wetland ecosystem in Minjiang River Estuary. Based on the SPRC assessment model and the vulnerability definition of IPCC, the vulnerability assessment index system of tidal flat slope, habitat elevation, vegetation coverage, average daily flooding time and deposition erosion rate index under the influence of sea level rise is established. Based on the vulnerability index system, the membership degree of the index calculated by the cloud model reflects the principle of quantification and operability (Zhu et al., 2019). This study can not only realize the spatial analysis to quantify the static vulnerability index on the ArcGIS platform, but also can dynamically simulate and predict the vulnerability of the coastal wetland in the Minjiang River Estuary under the influence of sea level rise in different scenarios in the future.

The coastal morphological evolution and the increase of average daily flooding time caused by rising sea level would affect the normal growth of plants in coastal wetlands (Chen et al., 2019). With the increase of sea level, the vulnerability of coastal wetlands increases accordingly in the study area (Fig. 7). Compared with low emissions, the vulnerability of coastal wetland increases under the scenario of high emissions. This conclusion is consistent with previous research results (Li et al., 2014; Cui et al., 2016; Shi et al., 2022). Although the simulation results in this study provide a fairly realistic set of predictions, we did not coupling future changes in wetland depositional dynamics, which

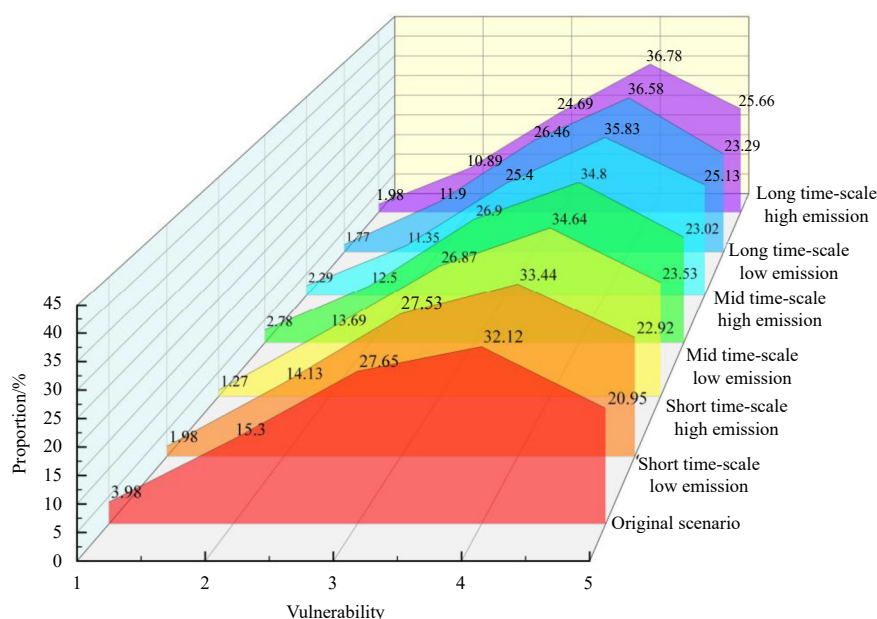


Fig. 7. Waterfall map of vulnerability proportion in each situation.

might affect the dynamic prediction of wetland ecological vulnerability in the study area. On one hand, Fujian coastal rivers bring a lot of sediment to the coastal wetland system. This is the key for wetland plant habitats to maintain suitable surface elevation, maintain gentle slope and mitigate the impact of sea level rise. On the other hand, due to sediment compaction, tectonic subsidence and land subsidence caused by excessive exploitation of groundwater, the relative sea level rise will be much higher than this value (Xu, 2020). Existing studies show that the global wetland ecosystem is generally undergoing a process of surface subsidence (Wang et al., 2021). The low original elevation of plants and the rise of sea level make some lowlands submerged. Exceeding the submergence tolerance height causes some plants to die. Vegetation coverage decreased. Coastal wetland vulnerability increased.

In addition, the coastal wetland is vulnerable to human activities and the degradation of the ecosystem's own state and recovery capacity shows a certain ecological vulnerability (Qi et al., 2020). Due to the influence of human activities and social and economic development, the change of sediment discharge in Minjiang River Estuary has great uncertainty. For example, the construction of reservoirs, dams and other water conservancy projects, coastal projects or reclamation projects cause local sediment deposition, which has the effect of blocking sediment, and a large number of river sand mining, resulting in a decrease in river sediment transport (Ministry of Water Resources of the People's Republic of China, <https://www.mnr.gov.cn/sj/sjfw/hy/>). In the future, the increase of coastal wetland erosion rate will further lead to coastal zone erosion and aggravate the impact of sea level rise on coastal wetland.

The implementation of effective sediment management and carbon emission management (Chen et al., 2019), to a certain extent, to slow down the rate of sea level rise, to carry out coastal wetland restoration and reconstruction projects, and to control large-scale reclamation are practical coping strategies and measures to cope with the impact of climate change on the coastal wetland ecosystem in the Minjiang River Estuary, Fujian Province. It is also a guarantee for maintaining the social and economic development of the coastal zone in the region, the quality of human production and life, and the safety of the coastal wetland ecosystem.

6 Conclusions

(1) From the perspective of the time course, the area of high vulnerability in the study area continues to increase with the time scale. And the area of low vulnerability shows a decreasing trend. Among them, the proportion of high vulnerability area of coastal wetland reached a maximum of 25.66% under long-term high emission scenario. In addition to the original scenario, the short-term low-emission scenario coastal wetland low vulnerability and the lower vulnerability area accounted for the largest proportion.

(2) From the perspective of spatial process, the eastern and northeastern parts of the Culu Island in the Minjiang River Estuary of Fujian Province and the eastern coastal wetland of Meihua Town in Changle District belong to areas with high vulnerability risk. The proportion of high vulnerability areas of coastal wetland increased with the increase of time and the carbon emissions. For the western and northern coastal wetlands of Meihua Town, the eastern part of Langqi Island, the southern part of Chuanshi Island, Culu Island, and the wetland between Langqi Island, the vulnerability to increased emissions over time also showed a clear upward trend.

(3) The results of this study indicated that elevation has the greatest impact on the vulnerability of coastal wetlands under different sea level rise scenarios, and the slope has less impact. The influence of sea level rise caused by climate change in the study area is mainly manifested in the sea level rise, which changes the habitat elevation and the daily average flooding time of coastal wetland. And it affects the survival and distribution of coastal wetland ecosystem. The slope of the tidal flat in the study area is basically less than 1, which is relatively gentle and has little impact on the vulnerability of coastal wetlands. The vegetation coverage has a great indirect impact on the long-term sequence. With the increase of sea level, the average daily flooding time of plants increases. It exceeds the flooding time and height of plants, thus affecting the vegetation coverage. This study predicts the vulnerability of coastal wetlands under different time sequences, which can provide scientific basis for formulating practical coping strategies and measures.

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Appendix A

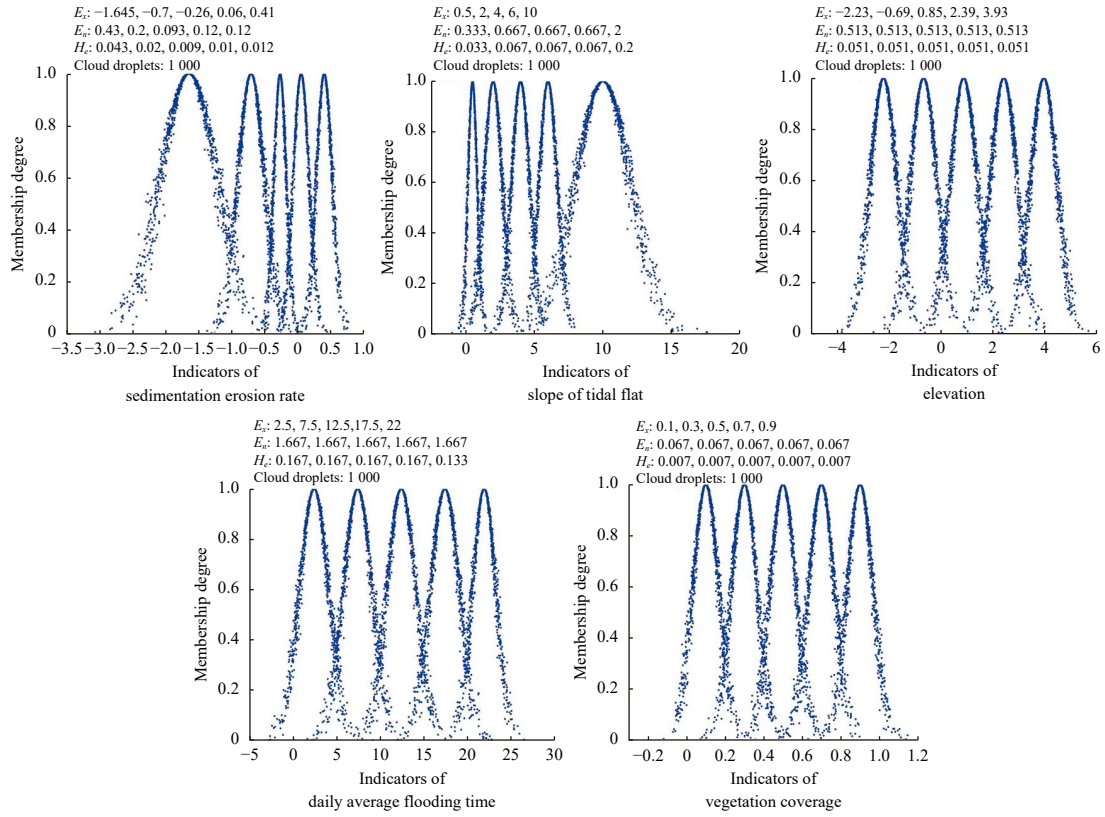


Fig. A1. Cloud diagram in short time series low emission situation.

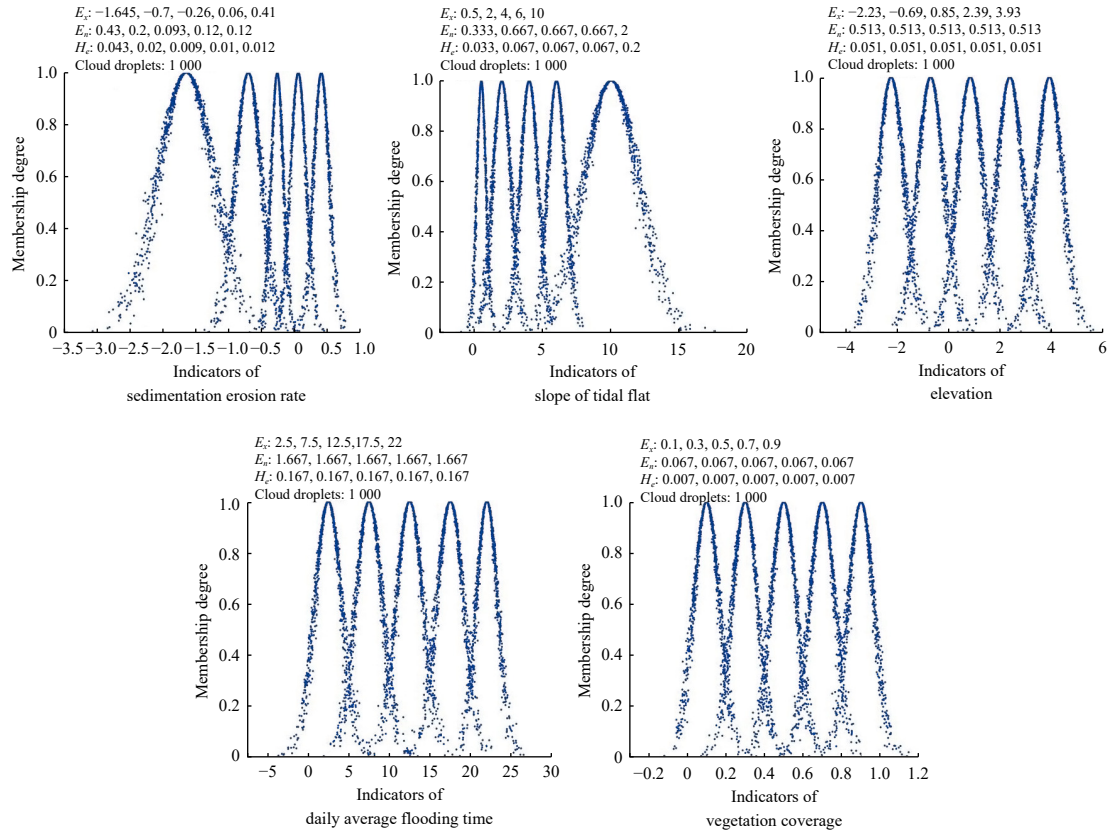


Fig. A2. Cloud diagram in short time series high emission scenario.

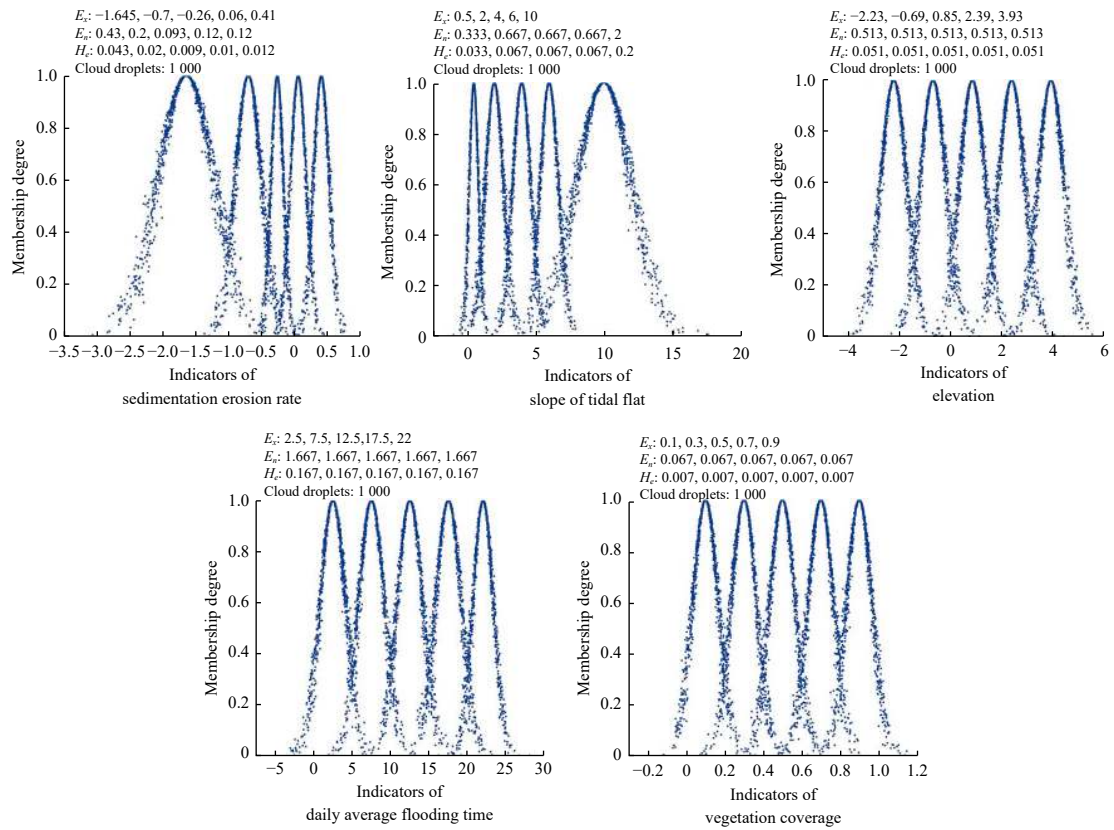


Fig. A3. Cloud diagram in medium timing low emission scenario.

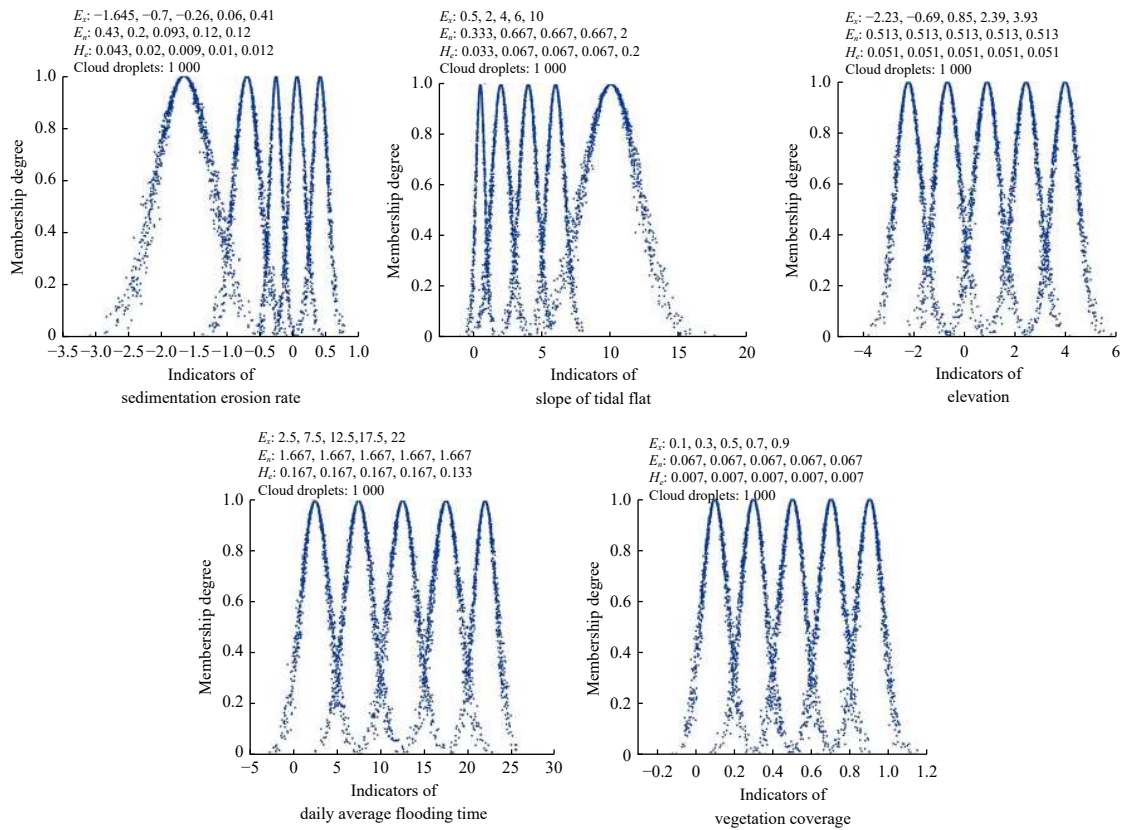


Fig. A4. Cloud diagram in medium timing high emission scenario.

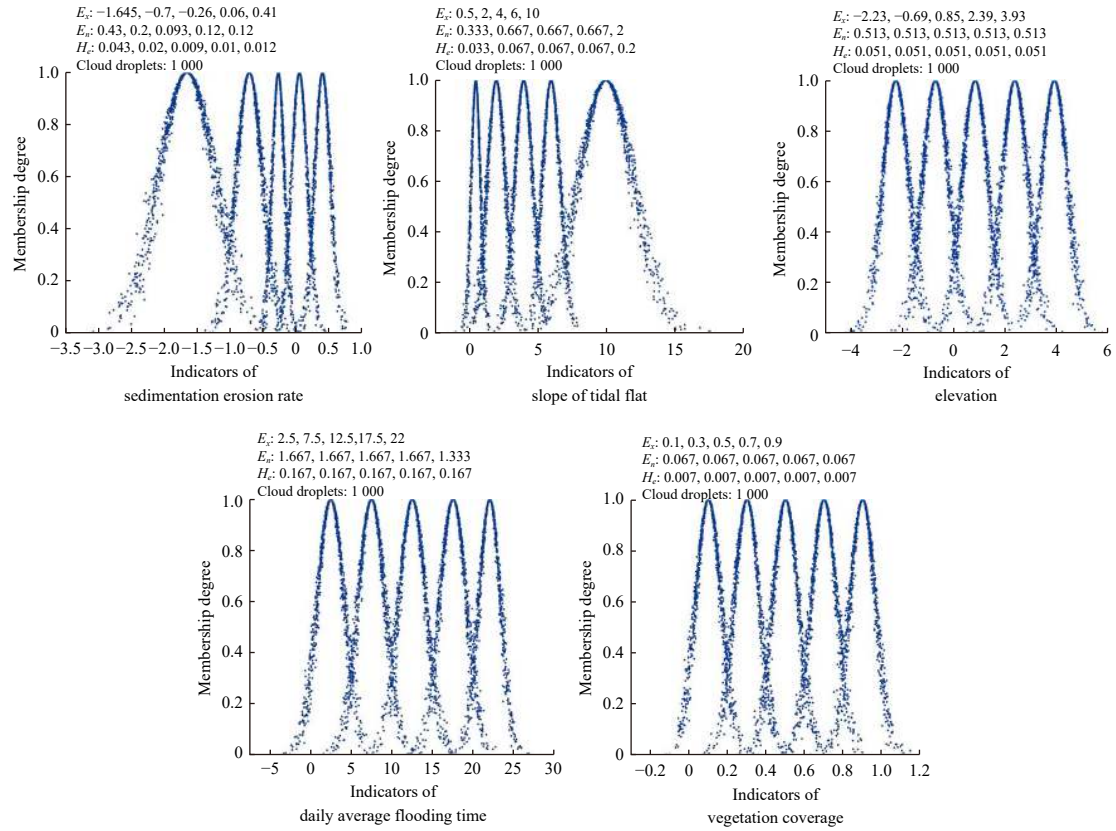


Fig. A5. Cloud diagram in long time series low emission situation.

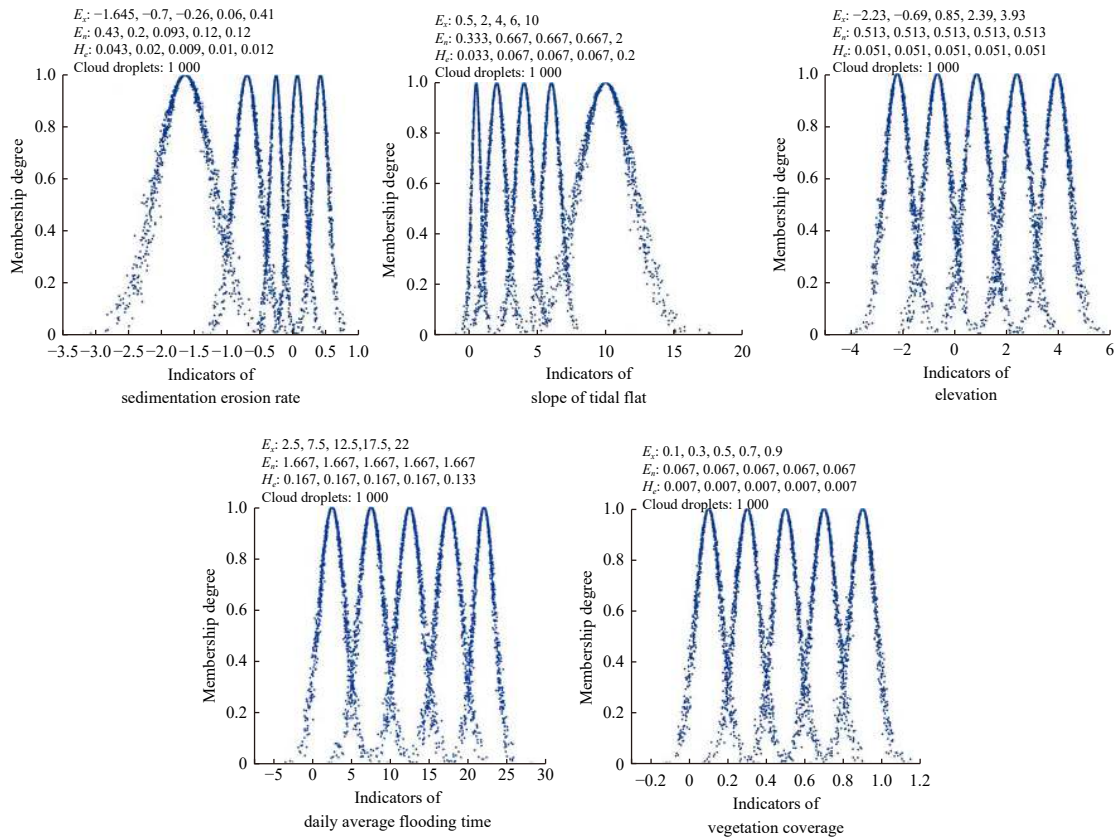


Fig. A6. Cloud diagram in long time series high emission situation.

Table A1. Cloud model index parameter table (E_x, E_n, H_e)

Grade index	Micro-degree	Slight	Moderate	Gravity	Utmost
Elevation/m	[−2.23, 0.513, 0.051]	[−0.69, 0.513, 0.051]	[0.85, 0.513, 0.051]	[2.39, 0.513, 0.051]	[3.93, 0.513, 0.051]
Daily average flooding time/ (h·d ^{−1})	[2.5, 1.667, 0.167]	[7.5, 1.667, 0.167]	[12.5, 1.667, 0.167]	[17.5, 1.667, 0.167]	[22, 1.333, 0.133]
Slope of tidal flat/(°)	[0.5, 0.333, 0.033]	[2, 0.667, 0.067]	[4, 0.667, 0.067]	[6, 0.667, 0.067]	[10, 2, 0.2]
Vegetation coverage	[0.1, 0.067, 0.007]	[0.3, 0.067, 0.007]	[0.5, 0.067, 0.007]	[0.7, 0.067, 0.007]	[0.9, 0.067, 0.007]
Sedimentation erosion rate/(cm·a ^{−1})	[−1.645, 0.43, 0.043]	[−0.7, 0.2, 0.02]	[−0.26, 0.093, 0.009]	[0.06, 0.12, 0.01]	[0.41, 0.12, 0.012]