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Article

Vulnerability of the Upper Coast of the Gulf of Thailand

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Abstract. Mangrove forests are vital ecosystems as they serve as a vital link between terrestrial and marine environments. They act as natural barriers against winds, waves, and erosion, protecting coastlines. Therefore, this study focuses on the extensive mangrove forest as one of the factors in assessing the coastal vulnerability index in the upper Gulf of Thailand. Geographic information systems (GIS) were utilized to analyze the levels of vulnerability, which were divided into five categories, ranging from very low vulnerability (level 1) to very high vulnerability (level 5). The study considered seven variables influencing vulnerability, including coastal slope, shoreline change rate, significant wave height, mean sea level rise, land use, population density, and mangrove forest width. The results of the study indicate that the majority of the coastline has a very low vulnerability level, covering an area of approximately 42.19 square kilometers (41.5% of the total area). The next level is high vulnerability, covering an area of 19.60 square kilometers (19.3% of the total area). The moderate vulnerability level covers approximately 15.85 square kilometers (15.6% of the total area). The low vulnerability level covers an area of about 14.04 square kilometers (13.8% of the total area). Lastly, the very high vulnerability level covers an area of 9.88 square kilometers (9.7% of the total area). The variables that have the most influence on the high vulnerability level are mangrove forest width, population density, and land use, in that order. This study provides valuable information for integrated coastal zone management to ensure the long-term sustainability of coastal areas.

Keywords: Coastal vulnerability, Upper Gulf of Thailand, erosion, mangrove.

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1. Introduction

Coastal areas are extremely important to the society and economy of a country. Coastal lands are rich in diverse natural resources, which are valuable both as natural ecosystems, as sources of food, and as resources crucial to humanity. However, coastal areas are among the most sensitive to changes [1]. Coastal areas are increasingly subjected to various threats resulting from climate change and anthropogenic activities. These factors have contributed significantly to the problem of coastal erosion [2]. Historically, changes in the coastline occurred gradually through natural processes, with the coast continuously adjusting to maintain equilibrium. Coastal erosion refers to the process that causes the coastline to retreat landward. Factors contributing to coastal erosion include waves, wind, currents, tides, sediment movement, and sediment accumulation along the coast, which lead to alterations in the original coastline. Coastal erosion in Thailand is a significant problem that causes damage to tourist sites, habitats, and ecological integrity, resulting in substantial economic losses for the country as a whole [1].

Climate change has significantly impacted the climate system and the marine environment, accelerating coastal erosion and altering shoreline configurations. These changes are driven by both climate change and human activities. Southeast Asia is one of the most vulnerable regions due to its extensive coastlines and high population density. Coastal areas in this region have repeatedly experienced natural disasters, including tsunamis, typhoons, and the continuous rise in sea level [3]. Research on coastal vulnerability has gained increasing attention since the mid-20th century, particularly following the 2004 Indian Ocean tsunami, which served as a major turning point in promoting more effective coastal management. Nevertheless, the impacts of climate change on both the environment and human communities have continued to intensify, especially in coastal areas of Thailand, where diverse physical and economic characteristics are observed [4]. Therefore, it is essential to integrate social, economic, and cultural factors alongside disaster-related data to ensure that recovery processes are sustainable [5]. Moreover, growing attention has been directed towards the study of natural coastal defense systems, such as mangroves, coral reefs, and seagrass beds. These ecosystems have been shown to play a significant role in mitigating the impacts of storm surges and tsunamis.

The Department of Marine and Coastal Resources has studied and developed approaches to address the issue of coastal erosion by relying on the principles of beach processes and sediment balance. They have divided the coastal areas into smaller units for more effective coastal management. According to these principles, the boundaries of each unit, known as a Littoral Cell, are defined based on geomorphological features, geological characteristics, and physical attributes. Each Littoral Cell is expected to maintain its sediment balance and prevent sediment from moving between different beach groups [6].

The Littoral Cell U encompasses the coastal area of the Upper Gulf of Thailand, stretching from Laem Phak Bia in Ban Laem District, Phetchaburi Province, to Ang Sila in Mueang Chonburi District, Chonburi Province [7]. This region is predominantly characterized by mudflats and dense mangrove forests. Mangroves function as natural barriers against waves and wind from the sea, acting as a protective shield against coastal erosion caused by waves and helping to maintain the coastal ecosystem's balance. They mitigate the impact of storms and can self-repair when damaged [8]. However, in recent times, these mangrove areas have been converted for other uses, such as aquaculture. The reduction in mangrove coverage has led to a lack of natural barriers to absorb wave energy, making the coast more susceptible to erosion [9]. Consequently, the width of the mangrove forest has been used as a factor in assessing coastal vulnerability to erosion in the Upper Gulf of Thailand. This assessment aims to study the vulnerability index of the coastal areas in the Upper Gulf and analyze the factors contributing to coastal erosion in the region.

The Coastal Vulnerability Index (CVI) is an important tool for assessing the vulnerability of coastal areas to environmental factors. Developed in 1990 by [10], the CVI was initially designed to evaluate the risk associated with rising sea levels along the eastern coast of the United States. It uses six physical variables as indicators of coastal vulnerability: geomorphology, coastal slope, sea-level rise rate, rate of coastal erosion/deposition, average tidal range, and average significant wave height. After ranking these factors, a mathematical formula is applied to determine the risk for each coastal area. Gornitz's study used the square root of the six variables in the calculation. Gornitz recognized that the effectiveness of the CVI could be enhanced by including indicators related to storm frequency and at-risk populations [11]. The CVI developed by Gornitz demonstrates the relationship between vulnerability and the sensitivity of coastal systems. It has since been widely accepted as a valuable tool for assessing the impact of environmental factors on coastal areas. The CVI uses Geographic Information Systems (GIS) to analyze the level of coastal vulnerability. Over time, it has been adapted and applied extensively in coastal regions worldwide. With only minor adjustments to make the methods more appropriate, the original approach retained its core focus on ranking and quantitatively assessing coastal vulnerability. In 2001, [12] further developed the CVI by dividing the variables into two groups: geological variables and physical process variables. This was done to create a coastal vulnerability map assessing the impact of sea-level rise along the Cape Cod shoreline. Subsequently, both physical and social factors were integrated, resulting in a more comprehensive assessment of vulnerability. This approach aligns with the [13], which highlights that the vulnerability of an area leading to disaster risk is not solely due to natural factors but also involves human development practices and adaptation strategies [14]. This knowledge will aid in effective coastal management, enabling the prioritization of management efforts, particularly in high-risk areas that may be affected in the future [15]. Moreover, the results of the vulnerability assessment reveal factors contributing to changes in the coastline. Given its effectiveness, researchers are now applying the CVI to study coastal erosion vulnerability in the Upper Gulf of Thailand. This research aims to evaluate the coastal vulnerability index for the region and analyze the factors contributing to coastal erosion in the upper Gulf of Thailand.

2. Study Area

The study area covers the coastline of the Upper Gulf of Thailand, following the principles of littoral-cell system boundary determination. It spans from the shoreline of Ang Sila Subdistrict, Mueang Chonburi District, Chonburi Province (CBI), passing through Bang Pakong District, Chachoengsao Province (CCO), continuing through Bang Bo District, Samut Prakan District, Phra Samut Chedi District, Samut Prakan Province (SPK), and further through Bang Khun Thian District, Bangkok (BKK), passing Mueang Samut Sakhon District, Samut Sakhon Province (SKN), Mueang Samut Songkhram District, Samut Songkhram Province (SKM), and finally reaching Laem Phak Bia Subdistrict, Ban Laem District, Phetchaburi Province (PBI), as shown in Fig. 1.The littoral-cell system of the Upper Gulf of Thailand consists mainly of mudflats and mangrove forests. Additionally, this area has diverse land uses, such as salt farms along the Mae Klong River, aquaculture at the mouths of the Mae Klong and Chao Phraya Rivers, industrial zones in Samut Prakan Province, and tourist attractions in Chonburi and Phetchaburi Provinces.

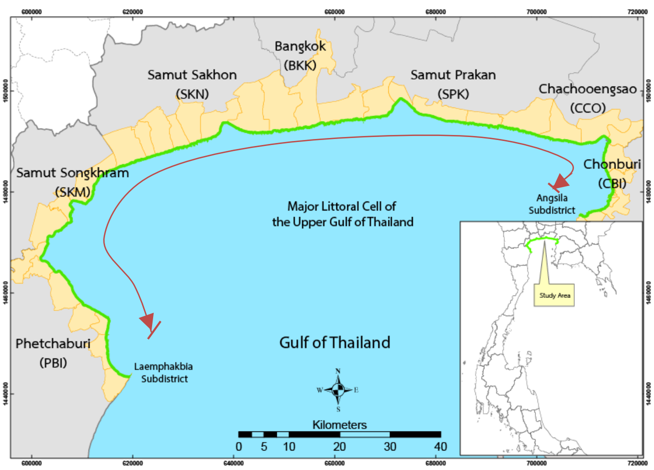

Fig. 1. Major Littoral Cell of the Upper Gulf of Thailand.

The inland boundary of this study extends 500 meters inland, as this area is within the influence of the coastline and has related land uses or impacts directly affecting the coastal area. This approach is similar to a previous study [16], which monitored changes along the Thai coastline by applying space technology and geoinformatics for the management of marine and coastal natural resources and the environment. The study also assessed the Coastal Vulnerability Index (CVI) as a central database for monitoring overall changes in coastal areas.

3. Material and methods

3.1. Data used for the study

The Coastal Vulnerability Index (CVI) from [10] demonstrates the relationship between the vulnerability of coastal systems to change and their ability to adapt to environmental changes. The original CVI variables from [10] have been widely applied in various studies, with some minor adjustments to the methodology to ensure appropriateness, while maintaining the original essence of the approach. This involves the ranking and quantitative assessment of coastal vulnerability. Preliminary research revealed three related studies on coastal vulnerability assessment, which included erosion rates as a variable. These studies were conducted at the provincial level, focusing on areas in Phetchaburi, Samut Songkhram, and Samut Sakhon provinces.

This study utilized data collected and compiled from multiple sources, including the following data sets:

(1) Coastal Slope Data: This data set is based on the Digital Elevation Model (DEM), specifically using the ASTER GDEM with a 30-meter resolution. The data can be downloaded from the website https://earthexplorer.usgs.gov/ in raster format. The slope was calculated using ArcGIS 10.5, with vulnerability classification criteria referenced from [17] and [18].

(2) Shoreline Change Data: This data set was compiled using aerial imagery from Google Earth by comparing the coastline from the years 2016 and 2019. The comparison was performed using the Overlay Technique within the Geographic Information System (GIS) software ArcGIS. This method allows for the calculation of areas that have experienced erosion or accretion. Additionally, the Digital Shoreline Analysis System (DSAS), an extension of ArcGIS, was used. The vulnerability classification criteria were referenced from [19].

(3) Significant Wave Height Data: This data set was obtained using the Ocean Wave Forecast Model (WAM Model), with data provided by the Marine Meteorological Center, Department of Meteorology. Representative points were selected for measuring wave height in each coastal province, using data from the past five years (2015-2019). The data includes wave heights recorded every three hours, and the average annual significant wave height was calculated. The five-year significant wave height averages were then computed to represent the study area in each location. The vulnerability classification criteria were referenced from [17] and [18].

(4) Mean Tidal Range Data: This data set was compiled from tidal gauge stations covering the coastline of the study area, with data collected between 2005 and 2014. The data was obtained from tide gauge stations operated by the Marine Department and the Hydrographic Department. These stations include Ao

Udom, Bang Pakong River Mouth, Chao Phraya River Mouth, Samut Sakhon, Ban Laem, and Hua Hin stations. The vulnerability classification criteria were referenced from [17] and [18].

(5) Population Data: This data was obtained from the Department of Provincial Administration, Ministry of Interior, for the year 2019. The population data was categorized by administrative levels down to the sub-district level. The population density was then calculated as the ratio of the population in each sub-district to its area. The vulnerability classification criteria were referenced from [18].

(6) Land Use Data: This data set includes land use information by district for coastal areas in the year 2019, provided in a digital geographic information system (GIS) database format by the Land Development Department. The vulnerability classification criteria were referenced from [20].

(7) Mangrove Width Data: This data set includes land use information by district for coastal areas in 2019, provided in a digital GIS database format by the Land Development Department. Coastal trees and mangroves etc., is a crucial natural barrier, protecting coastal areas from strong waves, flooding and erosion [21]. Given that the study area consists of mudflats, which are conducive to mangrove growth, this study considers mangrove width as a key factor. The vulnerability classification criteria are based on the impact of the December 26, 2004 tsunami, which caused significant damage to coastal areas in southern Thailand, including mangroves that were directly impacted by the waves [22]. However, in areas with dense mangrove forests, damage extended no more than 40 meters inland from the coast, contrasting with several hundred meters in areas without mangroves [23]. Similarly, in Japan, it was found that coastal forests approximately 200 meters wide could serve as effective barriers to reduce tsunami impacts [16]. Additionally, [24] studied the interaction between tsunami waves and mangroves, assessing their effectiveness in reducing wave runup. The study found that width and density of coastal vegetation contribute to the attenuation of tsunami run-up, with vegetation width playing a more significant role. A wider vegetated zone was found to be more effective in dissipating incoming wave energy. Specifically, a 1-meter width of mangrove forest reduced tsunami run-up by approximately 23–32% during high tide and 31–36% during low tide. Expanding the mangrove width to 2 and 3 meters further enhanced the average reduction in run-up to 39–50% and 34–41% during high and low tide conditions, respectively. Therefore, mangrove width is considered the most critical factor in reducing natural disaster risks. The vulnerability classification criteria for all variables used in this study are summarized in Table 1.

3.2. CVI calculations

After gathering the data for the study, the information was input into ArcGIS software, which was used as the primary tool for analyzing the Coastal Vulnerability Index (CVI). The levels of vulnerability were categorized into five levels, adapted from [25], as follows:

Level 5: Very High Vulnerability

This level indicates an unacceptable degree of vulnerability, with potentially severe and significant impacts. Immediate intervention and urgent corrective measures are necessary to prevent or mitigate these impacts.

Level 4: High Vulnerability

This level indicates a high degree of vulnerability that is unacceptable. It may lead to severe impacts. While immediate intervention may not be necessary, corrective actions are required to reduce the vulnerability to an acceptable level.

Level 3: Moderate Vulnerability

This level indicates a moderate degree of vulnerability, where the severity is not very high but still could have a noticeable impact. Continuous monitoring is required to control the situation and to reduce the vulnerability to an acceptable level.

Level 2: Low Vulnerability

This level indicates a low degree of vulnerability, which is relatively acceptable with mild and limited impacts. However, efforts should be made to control the situation to prevent the vulnerability from increasing.

Level 1: Very Low Vulnerability

This level indicates a very low degree of vulnerability, which is fully acceptable. No additional vulnerability management measures are necessary.

After assigning vulnerability scores to each variable, the factors are overlaid using tools from ArcGIS software. The Coastal Vulnerability Index (CVI) is then calculated using Eq. (1), with the calculation method in this study referenced from [10].

$$\text{CVI} = \sqrt{\frac{x_1 \times x_2 \times x_3 \times \ldots \times x_n}{n}} \tag{1}$$

where,

CVI is Coastal Vulnerability Index

x_n is the vulnerability level of each variable.

n is the total number of variables

Table 1. Classification of vulnerability variables.

Variable	Coastal Vulnerability Index Ranking				
	Very Low	Low	Moderate	High	Very High
Coastal Slope	>0.20	0.20–0.07	0.07–0.04	0.04–0.025	<0.025
Shoreline change	Erosion <1	-	Erosion 1-5	-	Accretion >5
Mean significant wave height	<0.55	0.55–0.85	0.85 –1.05	1.05–1.25	>1.25
Tidal range	<1.0	1.0–1.9	2.0–4.0	4.1–6.0	>6.0
Population	0–100	101–200	201–400	401–600	>600
Land use	Swamp forest/ Wetland/ Vacant land	Rangeland/ Coastal vegetation/ Mangrove forest	Forest land/ Evergreen forest/ Deciduous forest/ Agroforestry	Agricultural land/ Paddy field/ Crop field/ Horticultural field/ Pasture/ Aquacultural land	Residential/ Commercial/ Industrial/ Public utility & infrastructure
Width of the mangrove forest	>200	150–200	100–150	50–100	<50

The calculated values for each area are then classified into different vulnerability levels using a statistical method, specifically by calculating the percentile (P) of the data. The data, arranged in ascending order, is divided into 100 equal parts. This allows the vulnerability levels to be categorized as shown in Table 2.

Table 2. Vulnerability level data layer.

Coastal Vulnerability Index Ranking	Percentile Ranges
Very Low	0 - 20%
Low	20 - 40%
Moderate	40 - 60%
High	60 - 80%
Very High	80 - 100%

After categorizing the vulnerability levels based on the calculated data range of each variable, the results will be displayed as a Coastal Vulnerability Map for each coastal province in Thailand. The map will show different shades of color corresponding to different levels of vulnerability. Additionally, the key factors influencing the vulnerability level of each area will be determined by calculating the correlation coefficient (Correlation Coefficient: r) between the vulnerability level and the variables from Eq. (2).

$$\mathrm{r} = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}} \tag{2}$$

where,

r is Correlation Coefficient

x_i, y_i are the individual sample points indexed with i

$\bar{x}$ is the mean of the x - values

$\bar{y}$ is the mean of the y - values

4. Results

4.1. Evaluation of Coastal Erosion Vulnerability at Individual Levels

The coastal erosion vulnerability by level reveals that areas with very high vulnerability are most frequently found along the coast of Samut Sakhon province (2.54 square kilometers), followed by Samut Prakan province (2.46 square kilometers), and Phetchaburi province (1.58 square kilometers), respectively. However, when considering the proportion relative to the area of each province, Bangkok has the highest proportion of very high vulnerability areas compared to its total area (30.98%), followed by Chonburi province (12.07%) and Samut Sakhon province (11.50%), respectively.

The areas with high vulnerability are most frequently found along the coast of Samut Prakan province (8.04 square kilometers), followed by Samut Sakhon province (3.58 square kilometers), and Chonburi province (2.57 square kilometers). When considering the proportion of high vulnerability areas relative to the total area of each province, Samut Prakan province has the highest proportion (31.18%), followed by Bangkok (26.59%), and Chonburi province (23.70%), respectively.

The areas with moderate vulnerability are most frequently found along the coast of Samut Sakhon province (4.54 square kilometers), followed by Samut Prakan province (2.90 square kilometers), and Samut Songkhram province (2.62 square kilometers), respectively.

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When considering the proportion of medium vulnerability areas relative to the total area of each province, Chachoengsao province has the highest proportion (28.69%), followed by Samut Songkhram province (20.64%), and Samut Sakhon province (20.53%), respectively

The areas with low vulnerability are most frequently found along the coast of Samut Sakhon province (3.01 square kilometers), followed by Samut Prakan province (2.95 square kilometers), and Chonburi province (2.39 square kilometers), respectively. When considering the proportion of low vulnerability areas relative to the total area of each province, Chonburi province has the highest proportion (22.04%), followed by Chachoengsao province (19.30%), and Samut Sakhon province (13.67%), respectively.

The areas with very low vulnerability are most frequently found along the coast of Phetchaburi province (11.95 square kilometers), followed by Samut Prakan province (9.43 square kilometers), and Samut Sakhon province (8.45 square kilometers), respectively. When considering the proportion of very low vulnerability areas relative to the total area of each province, Phetchaburi province has the highest proportion (62.73%), followed by Samut Songkhram province (45%), and Samut Sakhon province (38.19%), respectively.

The summary of the study's findings is presented in bar charts, as shown in Figs. 2 and 3.

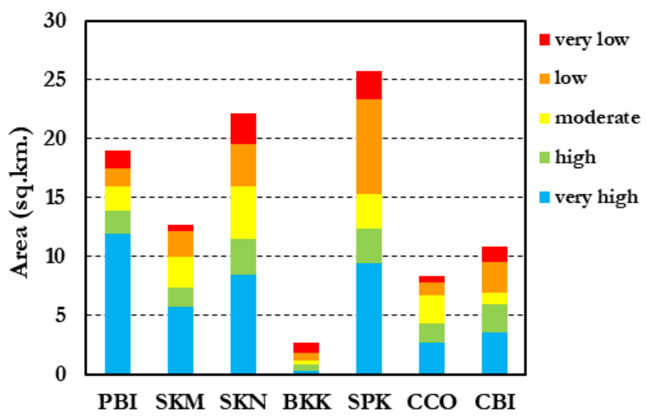

Fig. 2. Coastal vulnerable areas by province.

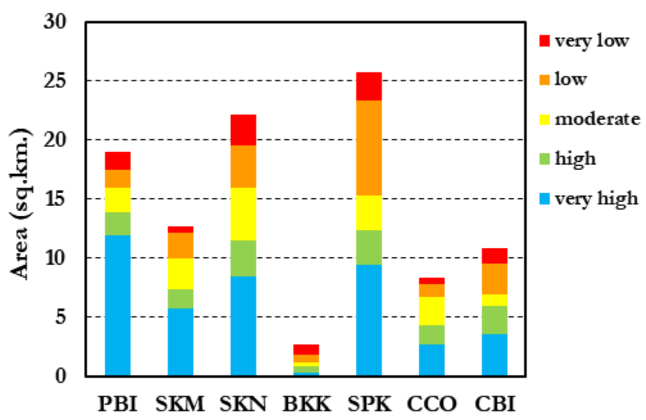

Fig. 3. The percentage of vulnerability to coastal erosion at each level is compared by province.

4.2. Evaluation of Coastal Erosion Vulnerability by Province

In the case of Chonburi province, the study of coastal erosion vulnerability found that the majority of the area has very low vulnerability (33.25%). The main factor influencing the vulnerability level of Chonburi's coast is population density. The secondary factor is land use variables, predominantly in areas classified as community and commercial zones, beaches, and tourism establishments in almost every sub-district:

In the case of Chachoengsao province, the study of coastal erosion vulnerability found that most areas have very low vulnerability (32.27%) and moderate vulnerability (28.69%). The main factor influencing the vulnerability level of Chachoengsao's coast is the width of the mangrove forest. This is due to the conversion of forest areas into aquaculture facilities, seaside restaurants, and the expansion of urban communities. Additionally, a large portion of the coastline in the Song Khlong subdistrict is facing erosion problems. The secondary factor is land use variables, with most of the coastal area consisting of mangrove forests, aquaculture ponds, and a few scattered coastal fishing communities near the canal mouths.

In the case of Samut Prakan province, the study of coastal erosion vulnerability found that most areas have very low vulnerability (36.58%). The main factor influencing the vulnerability level of Samut Prakan's coast is population density. Additionally, much of the coastline is facing erosion problems, including the coast of Bang Pu subdistrict and parts of the coast in Khlong Dan and Bang Pu Mai subdistricts. The secondary factor is land use variables along the coast, with the majority consisting of mangrove forests and aquaculture facilities, followed by industrial areas and residential communities.

In the case of Bangkok, the study of coastal erosion vulnerability found that there is very high vulnerability along nearly the entire coastline (30.98%). The main factor influencing this high vulnerability level is population density. The secondary factor is the width of the mangrove forest, as mangrove areas have been converted for other uses, such as aquaculture facilities.

In the case of Samut Sakhon province, the study of coastal erosion vulnerability found that most areas have low vulnerability (38.19%). The main factor influencing this vulnerability level is the width of the mangrove forest. However, much of the coastline is still characterized by very high vulnerability, including the coasts of Pantainorasingh, Kalong, and Nakhok sub-districts. Regarding land use, most of the coastal area is used for aquaculture. This condition is a significant factor contributing to the very high vulnerability of the coast in Khokkham and Phanthai Norasingh sub-districts.

In the case of Samut Songkhram province, the study of coastal erosion vulnerability found that most areas have very low vulnerability (45%). The main factor influencing this vulnerability level is the width of the mangrove forest, as the reduction in mangrove areas in Samut Songkhram, particularly in Laem Yai, Bang Chakreng, and Bangkaew sub-districts, is largely due to conversion for shrimp farming. The secondary factor is land use, with most coastal areas being used for aquaculture, followed by coastal community areas and a small amount of industrial zones. These conditions contribute significantly to the high vulnerability of the coastline in Laem Yai and Bang Chakreng sub-districts.

In the case of Phetchaburi province, the study of coastal erosion vulnerability found that most areas have very low vulnerability (62.73%). The main factor influencing this vulnerability level is the width of the mangrove forest. This is due to the reduction in mangrove areas in Phetchaburi, particularly in Pak Thale and Bangkaew sub-districts, where mangrove areas have been converted for shrimp farming. Additionally, these areas are used for residential purposes, communities, hotels, tourism, road construction, government buildings, and salt farming. The secondary factor is land use, as areas in Pak Thale and Bangkaew sub-districts are used for community zones, commercial areas, and industrial zones. This contributes to the very high vulnerability of these regions.

The details of the coastal erosion vulnerability assessment, categorized by province, are illustrated in Fig. 4. The results of the correlation coefficient analysis (r) between the vulnerability levels and various variables in the study area, as defined by Eq. (2), are presented in Table 3. The analysis of the correlation coefficients reveals that the significant wave height and tidal range variables exhibit no meaningful correlation with the Coastal Vulnerability Index (CVI) in the upper Gulf of Thailand system. This lack of correlation is attributed to the coarse spatial resolution of the datasets used for these variables, which results in uniform vulnerability levels across the entire study area when categorized. Additionally, the criteria for classifying vulnerability levels, as shown in Table 1—derived from a review of previous research—were found to have overly broad classification ranges. Consequently, the majority of data points within the study area fall into the same vulnerability class. This results in generally low to moderate correlation values between the input variables and the calculated CVI. It is acknowledged that such relatively weak correlations may be influenced by other factors not included in the current analysis but which may affect the dependent variables. Furthermore, the inherent complexity of coastal systems also plays a significant role. These issues highlight the need for more comprehensive and detailed future studies.

Although this study adopts the conceptual framework proposed by [10], it employs a different set of variables that reflect the specific characteristics of the study area. Gornitz's approach emphasizes geophysical and geological factors that represent long-term natural processes affecting coastal vulnerability. In contrast, this study considers not only physical factors but also incorporates biological and social components such as mangrove forests and land use which are essential for coastal planning and management. Therefore, coastal vulnerability assessment is a process that requires the careful selection of appropriate variables to accurately reflect the actual risks in different coastal contexts.

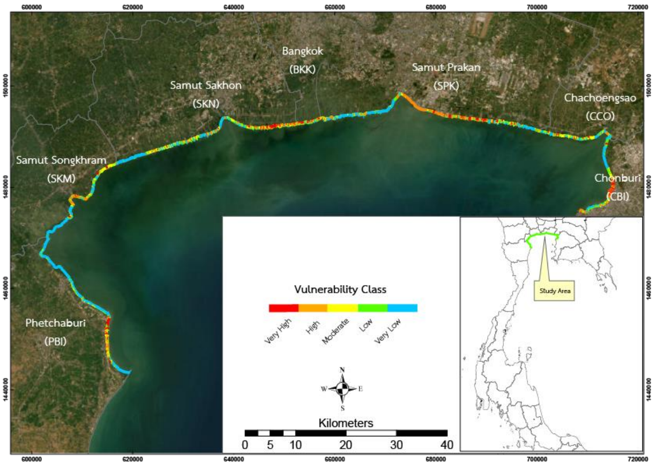

Fig. 4. The entire study area (the Littoral Cell U).

Table 3. Correlation coefficient of vulnerability levels with variables.

Variable	r
Coastal Slope	0.36
Shoreline change	0.17
Mean significant wave height	N/A
Tidal range	N/A
Population	0.55
Land use	0.43
Width of the mangrove forest	0.51

4.3. Relative Coastal Vulnerability Index: CVI′

As discussed in Section 4.2, one of the reasons for the limited correlation between the vulnerability index and individual variables lies in the broad classification intervals originally used to categorize coastal vulnerability. Additionally, in several areas, the computed CVI values were not sufficiently distinct to allow effective prioritization or categorization. To enhance the usefulness of this research in supporting decision-making for prioritizing vulnerable areas, a revised classification scheme was implemented. This involved reclassifying each variable using percentile-based thresholds derived from the study dataset. The vulnerability was divided into five intervals or levels to highlight the relative differences across the study area. The resulting index is referred to as the Relative Coastal Vulnerability Index (CVI′).

The criteria for classifying the vulnerability levels for CVI′ are shown in Table 4. A summary of the findings is presented in the bar chart in Fig. 5. A comparison between the original CVI and the revised CVI′, disaggregated by province, is provided in Fig. 6. It was observed that the reclassification allowed for a more dispersed distribution of vulnerability values, which, in some cases, increased the vulnerability classification of areas previously categorized as less vulnerable. Therefore, the CVI′ can serve as a more useful tool for decision-makers tasked with coastal protection and monitoring, particularly in areas with currently low apparent vulnerability. This enhances the effectiveness of management measures by enabling better-targeted interventions.

The analysis of the correlation coefficients (r) between vulnerability levels and contributing variables revealed that the top three influencing factors associated with highly vulnerable coastal zones remain consistent with the previous assessment. These are land use, population density, and mangrove width, as shown in Table 5, though their rankings may have shifted. The revised classification method also resulted in improved statistical correlations between the variables and the CVI′.

Consequently, coastal vulnerability assessment requires the careful selection of context-specific variables that appropriately reflect the true risks within a given setting. In the context of the upper Gulf of Thailand, future coastal erosion mitigation strategies should prioritize mangrove reforestation or expansion, as population density and land use are anthropogenic factors that are often difficult to alter or manage directly.

Table 4. Criteria for Classifying Variable Vulnerability Levels Used in the Calculation of CVI′.

Variable	Coastal Vulnerability Index Ranking				
	Very Low	Low	Moderate	High	Very High
Coastal Slope	>0.11	0.11–0.08	0.08–0.06	0.06–0.025	<0.025
Shoreline change	Erosion <1	-	Erosion 1-5	-	Accretion >5
Mean significant wave height	<0.22	0.22–0.23	0.23 –0.24	0.24–0.25	>0.25
Tidal range	<1.7	1.70–1.72	1.72–1.79	1.79–1.87	>1.87
Population	0–165	165–291	291–472	472–976	>976
Land use	Swamp forest/ Wetland/ Vacant land	Rangeland/ Coastal vegetation/ Mangrove forest	Forest land/ Evergreen forest/ Deciduous forest/ Agroforestry	Agricultural land/ Paddy field/ Crop field/ Horticultural field/ Pasture/ Aquacultural land	Residential/ Commercial/ Industrial/ Public utility & infrastructure
Width of the mangrove forest	>348	167–348	86–167	10–86	<10

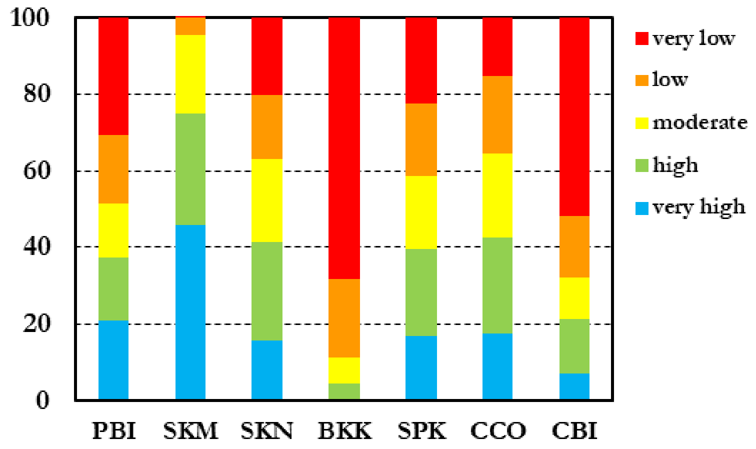

Fig. 5. The percentage of CVI′ at each level is compared by province.

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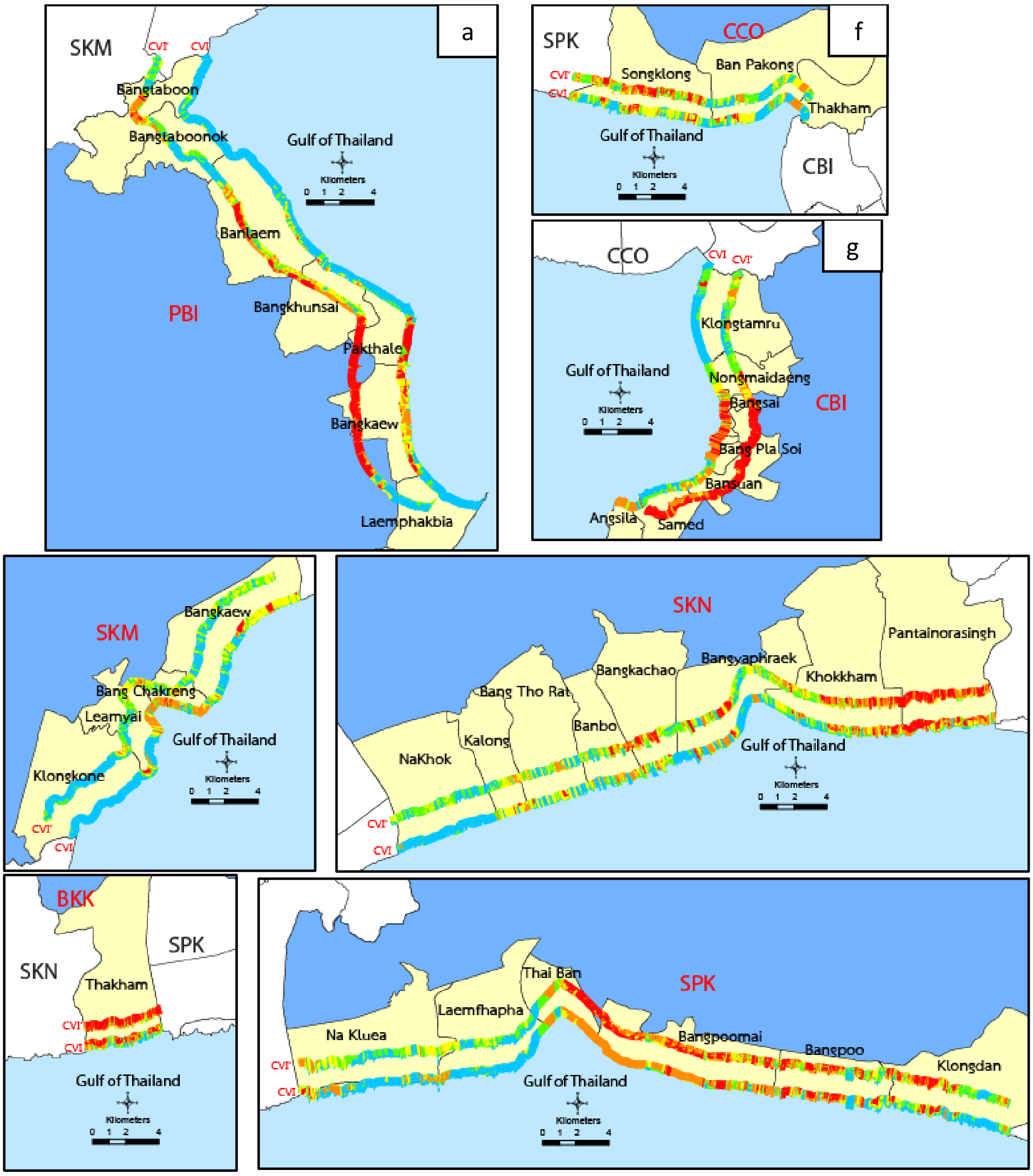

Fig. 6. Comparison of CVI and CVI′ by Province. (a: Phetchaburi Province; b; Samut Songkhram Province; c: Samut Sakhon Province; d: Bangkok; e: Samut Prakan Province; f: Chachoengsao Province; g: Chonburi Province).

Table 5. Correlation coefficient of CVI′.

Variable	r
Coastal Slope	0.32
Shoreline change	0.36
Mean significant wave height	0.32
Tidal range	0.37
Population	0.54
Land use	0.77
Width of the mangrove forest	0.40

5. Conclusions

The coastline in the Upper Gulf of Thailand mostly has very low vulnerability, with a total area of 42.19 square kilometers, representing 41.54% of the study area. This is most prominent along the coast of Phetchaburi province. The next category is high vulnerability, with a total area of 19.60 square kilometers, representing 19.30% of the study area, found mainly along the coasts of Chonburi province and Bangkok. Low vulnerability areas cover a total of 14.04 square kilometers, or 13.82% of the study area, most notably along the coasts of Chonburi and Bangkok. Medium vulnerability areas cover 15.85 square kilometers, or 15.61% of the study area, with the highest concentration along the coasts of Chachoengsao, Samut Songkhram, and Samut Sakhon provinces. Very high vulnerability areas cover 9.88 square kilometers, or 9.73% of the study area, predominantly along the coast of Bangkok. Analysis of the correlation coefficient (r) between vulnerability levels and variables, as shown in Table 3, indicates that the top three factors influencing very high vulnerability in coastal areas are population density, the width of the mangrove forest, and land use, respectively. To enhance natural coastal defense systems, the Coastal Vulnerability Index (CVI) which incorporates mangrove-related variables can be applied to support the conservation, protection, and restoration of mangrove forests. These areas serve as a natural buffer against wave and wind energy and are essential for mitigating coastal erosion. Furthermore, in areas where the original CVI classifications were not sufficiently distinct, the use of the Relative Coastal Vulnerability Index (CVI′) helps improve prioritization by providing greater clarity in vulnerability classification. This enables more effective planning, implementation of protective measures, and systematic monitoring of vulnerable coastal zones.

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