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Assessment of the Need for Maintenance of Coastal Protection Facilities and the Designation of Deteriorated Areas

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Abstract

This study proposes a systematic methodology to assess maintenance needs of coastal protection facilities and to identify shoreline segments suitable for retreat, designated as “Deteriorated Areas”. Using the Hualien coast of Taiwan as a case study, the approach integrates the Coastal Management Act and Spatial Planning Act into a structured evaluation framework. A coastal deterioration index was developed based on three key aspects: necessity, urgency, and feasibility, each represented by selected indexes. The Fuzzy Delphi Method (FDM) was applied to achieve expert consensus on these indexes, ensuring that both technical and socio-environmental priorities are incorporated into the assessment. Each index was quantified and assigned a score, which was then combined to calculate an overall index score for each coastal section. These scores were subsequently classified into five deterioration levels, from minor to extreme, with severe and extreme levels trigger retreat strategies. This methodology provides a transparent, data-driven process for prioritizing coastal adaptation measures, enabling authorities to effectively balance hazard mitigation, ecological restoration, and resource allocation. By directly linking deterioration assessment to retreat designation, the proposed framework offers a practical tool to support sustainable coastal management under increasing climate change pressures.

1. Introduction

The coastal zone is significantly impacted by climate change, especially through accelerated coastal erosion and flooding associated with rising sea levels and potentially more frequent extreme weather events. In response, the United Nations Framework Convention on Climate Change (Sands, 1992; Salman et al., 2004) eloquently delineates three adaption strategies for coastal regions: protection, accommodation, and retreat. These strategies are employed in coastal mitigation efforts worldwide (European Commission, 2004a, b).

In Taiwan, the Integrated Coastal Zone Management Program (ICZMP) (Ministry of the Interior, 2017) describes protection strategies as a set of preventive and contingency measures that align with hazard potential based on established design criteria. These include maintaining defense structures and monitoring changes in coastal bathymetry. However, the use of the land behind the defensive structure is ignored in defining protection criteria. Applying a single protection criterion to a diverse range of existing land uses is not appropriate (Huang et al., 2016, 2018). As for the accommodation strategy, it focuses on hazard reduction and prevention tailored to specific coastal areas. This may involve improving the effectiveness of early warning systems and regulating land use to minimize social vulnerability (Tang et al. 2023). If the protection and accommodation strategies prove insufficient to mitigate hazards or provide adequate protection, the retreat strategy can be implemented to prevent further loss (Wolff et al., 2023). Due to economic, political, and social pressures that often hinder the enforcement of retreat regulations, the retreat strategy has never been successfully implemented. That results in the government being obliged to maintain the function of all coastal defenses without distinction.

As the coast develops, the strategies implemented in the past should be adjusted accordingly. For existing coastal defenses that pose high hazards and lack specific protective properties, it is neither economically viable nor aligned with sustainable coastal management to continue investing in protective measures. Coastal setbacks are defined as a designated distance from a coastal feature, such as the shoreline or vegetation line, within which development is either restricted or prohibited (Cambers, 1998; Fenster, 2005; Sánchez-Arcilla et al. 2016). It can be used as a spatial planning mechanism to implement the retreat strategy incrementally or preemptively. Adopting the retreat strategy for ineffective defenses by designating a setback line makes it possible not only to allocate of funding effectively, but also to restore the natural shoreline in place of the structural one.

The concept of coastal setback lines has developed as a strategic method to manage and reduce risks associated with coastal hazards. Early guidelines from organizations like UNESCO highlight the importance of setbacks in safeguarding against coastal hazards while allowing for natural shoreline dynamics to occur. Various countries have implemented setback policies that are customized to their specific geographic and climatic conditions. For instance, Romanian legislation, along with that of Portugal and the Mediterranean Integrated Coastal Zone Management (ICZM) protocol, mandates the maintenance of a specified distance from the coastline to establish a setback zone. Within this zone, the development of infrastructure is prohibited, with the exception of critical energy facilities or waste management systems (Sanò et al., 2011; Pena et al., 2021). In the United States, 14 states have implemented setback zones that regulate construction activities. These zones are typically determined based on observed long-term erosion trends (Neal et al., 2018; Williams et al., 2018). New Zealand has developed a guide for establishing setback lines that considers various coastal hazards, including erosion and inundation, while also evaluating the potential impacts of the future sea level rise (Ramsay et al., 2012; Wainwright et al., 2014). At the opposite end of the coastal management spectrum is the strict adherence to maintaining the coastline's position. The strategies in place in the Netherlands and Poland exemplify this approach. In both countries, regulations have been established to ensure that all actions related to coastal protection are undertaken at a level that preserves the coastline's position from 1990 in Poland (and from 2003 in the Netherlands) (Brand et al., 2025; Boniecka and Kubacka, 2024; Cieślak 1992). Moreover, Polish regulations have introduced designated technical and protective zones where construction is only permitted after obtaining approval from the relevant authority responsible for issuing building permits. In practice, this means that within a zone approximately 300 to 800 meters wide, no construction can take place except for structures serving coastal protection purposes. Additionally, both the Netherlands and Poland specify which coastal protection methods, such as beach nourishment, revetments, and groins can be applied to different sections of their coastlines. However, discussions are ongoing in both countries concerning the increasing effects of rising sea levels, particularly from the North Sea and the Baltic Sea. In Poland, this has led to considerations of moving away from strict adherence to the 2003 coastline position. Due to ongoing erosion, there is a possibility that the strategy for the period from 2027 to 2047 may adopt the 2015 coastline as the new reference line. Regardless, the concept of managing deteriorated coastal areas is gaining traction globally and is becoming increasingly important in coastal protection strategies. These policies have

assessed both the current and future potential impacts of various coastal hazards, and they have either restricted development or acquisition within designated setback areas without bias. However, public opposition poses a significant challenge to implementing these setbacks, particularly when community members feel that the setbacks do not meet their expectations (Zhu et al., 2010). This apprehension is especially prevalent among individual landowners whose properties are affected by the newly designated restricted development zones. Furthermore, agencies responsible for managing retreats that require land to be yielded to the sea may encounter resistance due to the high costs involved and the prevailing perception that they are relinquishing valuable coastal land. Therefore, to effectively promote coastal setbacks, it is essential to evaluate not only the impact of hazards but also the land use status within these setback areas. Moreover, when designing these setbacks, it is crucial to consider the stakeholders' perceptions of coastal hazards and their willingness to accept relocation.

The variety of coastal characteristics and developments subject to different kinds of coastal hazards lead to myriad combinations of impacts on socioecological aspects. This complexity makes it challenging to draw setback lines. The over-simplification and misapplication of insufficient coastal hazard data in planning yields results that are often incomplete and do not meet the needs. Horton and Britton (2015) indicated that establishing the setback line should be guided by a comprehensive risk assessment. They considered various coastline hazard lines along with the design life of building structures. Rather than applying multiple lines and zones with varying planning periods and undefined probabilities, they proposed a single probabilistic "acceptable risk" line for a specified planning period.

Mapping a variety of hazardous coastal areas by Geographic Information System (GIS) techniques is essential for effective coastal area management. This process begins with assessing and mapping coastal risks in order to prioritize interventions. Risk refers to potential consequences that may arise when something of value is at stake, with outcomes that are uncertain. It is often represented as the probability of hazardous events occurring, multiplied by the potential impacts of these events (IPCC, 2014, 2019; Kirby et al., 2021). Several methodologies are used to quantify the coastal risk index, which can be categorized into geophysical, social, and socio-environmental contexts (Nguyen et al., 2016; Zanetti et al., 2016; Rocha et al. 2023). By employing these methodologies, we can clearly evaluate the potential threats that coastal hazards pose to both the natural environment and the residents of coastal areas.

The U.S. Army Corps of Engineers (2023) developed an economic justification plan aimed at reducing damage to structures and infrastructure along the coast of Puerto Rico. This plan addressed the threats posed by coastal hazards while also considering social impacts, economic development, and environmental quality, as these factors are crucial for its success. Ranasinghe et al. (2012) demonstrated that determining the economically optimal coastal setback line, which integrates an economic risk model, can distinctly quantify risks associated with coastal erosion.

Coastal defenses are designed to protect human lives and properties. However, when these protective structures lose their effectiveness, or when the cost of maintaining them exceeds the value of the

protective assets, it becomes necessary to develop a retreat strategy and establish a setback line. Effective planning for setback line zoning requires a comprehensive understanding and analysis of current and future coastal hazard data, as well as community engagement and economic feasibility. Without these elements, the planning process for setback lines will remain merely theoretical. Therefore, feasibility should be addressed at the initial planning stage. The primary goal of this study is to propose a scientific and analytical methodology for evaluating shoreline segments with shoreline protection to identify protective structures for removal or abandonment and to designate an appropriate setback line.

2. Background

2.1 Study area

Taiwan has been actively developing its coastal areas, and following a surge in its economy during the 1970s, much of the necessary infrastructure and coastal defenses have been established. However, a conflict has emerged between the exploitation of these areas and the need for nature conservation. As a result, the implementation of the Integrated Coastal Zone Management (ICZM) plan was delayed until 2017. By designating coastal protection zones and reserves, the use of coastal areas has been aligned with the principles of sustainable development.

In recent years, climate change has heightened the risks of hazards in coastal regions, leading to significant challenges and funding pressures for coastal defenses. The Hualien coast in eastern Taiwan is particularly exposed to shoreline erosion and is frequently affected by typhoons due to its location along the typhoon route in the western Pacific Ocean. Figure 1 shows the locations of coastal defences and distribution of settlements along the Hualien coast. This coast is known for its natural landscapes and features only a few anthropogenic developments. Aside from a handful of larger settlements, most communities are dispersed along the coastline.

This vulnerability puts the region at risk for severe weather events, leading to increased public demand for stronger protective measures. As climate change progresses, the threat of coastal erosion in certain areas is expected to grow, highlighting the urgent need for investment in protective strategies. However, urbanization and out-migration have led to a rapid decline in the population of several dispersed settlements, while costs associated with protecting these areas are on the rise. Meanwhile, some eroded coastal sections continue to deteriorate, and eliminating the threat will require further investment, which could have adverse effects on the environment. Therefore, at the present stage, a scientific approach is needed to determine whether to implement the retreat strategy.

2.2 Legal regime

In recent years, the relentless onslaught of natural disasters driven by climate change has ravaged significant expanses of land, underscoring an urgent need for restoration efforts that safeguard both the environment and the well-being of local communities. In response to this pressing challenge, the Spatial Planning Act, enacted by the Ministry of the Interior in Taiwan in 2016, stands as a powerful testament to

our commitment to environmental restoration. This legislation establishes a robust legal framework that empowers authorities to take decisive action in advancing these critical initiatives.

As stipulated in Article 35 of the Act, areas at high risk of mudslides, severe landslides, and land subsidence, as well as regions where the watershed ecosystem is threatened, are designated as Environmental Restoration Promotion Areas. This designation extends to locations with severely damaged ecosystems, other geologically sensitive regions, and places where environmental conservation has suffered most profoundly.

The designation of Environmental Restoration Promotion Areas is based on three key principles: necessity, urgency, and feasibility. However, it is essential to note that the types of threats to coastal areas have not been adequately addressed within this framework, and the relevant ministries involved are different. In acknowledgement and response to these vulnerabilities and management needs in coastal regions, a legal framework for integrated management has been established through the enactment of the Coastal Management Act. This legislation is designed to promote Integrated Coastal Zone Management and sustainable development.

According to Article 7 of the Coastal Management Act, priority must be given to protecting natural coasts and maintaining ecological systems. This includes implementing building setbacks or adjusting land use to address climate change threats and coastal hazard risks. The Act represents a shift in Taiwan's approach to coastal protection, away from a traditional focus on preventing hazards toward a strategy that acknowledges hazards exceeding coastal defense criteria, while still maintaining those criteria or reducing risk through strategies such as retreat. The act provides public authorities with a legal basis to manage land use in the coastal zone. In hazardous areas, it is no longer necessary to rely solely on strengthening coastal protection. However, many of the existing directives and related guidance programs in Taiwan's coastal zones have only suggested the concept of retreat without establishing specific evaluation methods for determining setback lines.

Finally, the first comprehensive review of the Integrated Coastal Management Plan (Ministry of the Interior, 2025) has established a framework to integrate the Spatial Planning Act and the Coastal Management Act. This framework includes the potential designation of "Deteriorated Areas", which encompasses coastal protection zones, the 13 identified erosional hotspots (EHSs)(Kraus and Galgano, 2001; Huang 2022), and regions with eroded coastlines. Additionally, ecologically degraded areas should also be taken into account. In summary, deteriorated areas can be divided into two categories: 1) hazardous areas with low importance for protection objectives and 2) areas where the ecological environment has suffered serious damage and degradation.

To mitigate coastal hazards, retreat measures can be taken. The ecological functions of these coastal areas can gradually be restored, supporting the sustainable development of the region. Since Deteriorated Areas are not designated along the entire coast but are proposed by local governments, this approach is tailored to local conditions and suitable for effective implementation.

3. Methods

The study examines the coastal sector in Hualian that is safeguarded by coastal defenses to identify areas at high risk that currently lack adequate protective assets. The objective is to officially designate these locations as Deteriorated Areas by applying the concept of retreat strategies, which can help reduce the risk of coastal hazards. This can be achieved by revising land-use patterns and retreating from the protection line. Ultimately, the goal is to promote the effective utilization of protective resources and ensure sustainable operations.

To comply with the Spatial Planning Act and adhere to the regulations of the Coastal Management Act, we seek to identify Deteriorated Areas in accordance with Environmental Restoration Promotion Areas. These areas will be evaluated according to their necessity, urgency, and feasibility of designating them as Deteriorated Areas. Currently, there is no standardized database for Deteriorated Areas, so our study will utilize an index database from a coastal risk assessment developed by the Water Resource Agency. The indexes will be categorized according to the aspects of necessity, urgency, and feasibility to assess Deteriorated Areas effectively (see Table 1).

"Necessity" refers to the level of urbanization, the types of economic activities present, and the condition of infrastructure. Evaluation indexes include land use, the protection of residents, population density, vulnerable populations, economic industries, and the availability of emergency shelters. There is a relationship between "necessity" and "vulnerability" in risk analysis: as vulnerability increases, so does the level of risk. As population density and land use increase, vulnerability also rises, leading to a higher risk situation. However, high levels of vulnerability complicate the implementation of retreat strategies due to complex social and economic factors. This creates significant obstacles in designating Deteriorated Areas. As a result, there is an inverse relationship between vulnerability and necessity: the lower the vulnerability, the higher the necessity, which makes the designation of these areas more attainable.

"Urgency" can be regarded as a hazard level in risk analysis. The higher the hazard potential, the more likely it is that a given area will be designated as a Deteriorated Area. The evaluation indexes include: wave overtopping discharge for a 50-year return period, status of coastal defenses, rates of coastal erosion (Burningham and French, 2017), beach width, historical disaster records, public complaints, sea level rise, wave overtopping discharge under climate change scenarios, coastal hazard risks, and the designation of coastal protection areas.

Regarding " feasibility", we consider the technical viability of retreat, cost-effectiveness, land ownership compositions, and stakeholder opinions. Feasibility evaluation indexes include: relevant regulations and policies, ecological reservation areas, unauthorized or illegal land use, involved agencies, cost ratio of maintenance to retreat, land ownership, and public opinion.

In this study, The Fuzzy Delphi Method (FDM) (Murray et al., 1982; Ishikawa et al., 1993) is utilized for the preliminary assessment of indexes by experts, which aids in making the selection of representative

indexes both objective and practical. Recognizing that identifying Deteriorated Areas necessitates expertise in coastal environments and disaster prevention, the questionnaire survey specifically targeted disaster prevention officials, academics, and engineers. A total of 15 surveys were collected.

The FDM is a decision-making technique (Zavadskas et al., 2016) that merges fuzzy set theory with the classical Delphi method to better address uncertainty in expert opinions. This method effectively captures the fuzziness and uncertainty inherent in human thought processes, allowing for a reduction in the number of questionnaire iterations required, while more accurately reflecting experts' professional insights.

To consolidate expert opinions, "double-triangle fuzzy numbers" (Ma et al., 2011; Jeng, 2009; Chuang et al. 2024) are employed, and the "gray zone test method" is applied to verify the convergence of opinions. The following sections will provide a detailed explanation of the application process and the testing steps involved.

Initially, experts complete a questionnaire where they subjectively score various indexes on a scale from 0 to 10, with higher scores indicating greater importance. The "most pessimistic cognitive score" and the "most optimistic cognitive score" provided by all experts for each index are then statistically analyzed. Any extreme score that is beyond double the standard deviation is removed as an outlier.

Next, the lowest score C_L^i, the geometric mean score C_M^i, and the highest score C_U^i from the remaining “most pessimistic cognitive score” were calculated. Similarly, the minimum score O_L^i, the geometric mean score O_M^i, and the highest score O_U^i from the “most optimistic cognitive score” were also determined. Based on these results, the three-angle fuzzy number Ci=(C_L^i, C_M^i, C_U^i) for the “most pessimistic cognition” and the three-angle fuzzy number Oi O_L^i, O_M^i, O_U^i for the “most optimistic cognition” for each index *i* were derived, illustrated in Fig. 2.

The level of consensus achieved by the experts is determined by the overlap between two triangular fuzzy numbers. When there is no overlap (i.e., no gray zone), the consensus score G_i for evaluation index *i* equals the arithmetic mean of C_M^i and O_M^i.

If an overlap between the two triangular fuzzy numbers is observed and the gray zone Z^i is smaller than the interval range M^i, then the consensus score for index *i* can be determined through to the intersection of the two triangular fuzzy numbers. The quantization score of the fuzzy set with the highest membership score is used.

Where

$$Z^i = C_U^i - O_L^i$$

1

$$M^i = O_M^i - C_M^i$$

2

If an overlap is observed and the gray zone Z^i is larger than the interval range M^i, another round of the survey will be conducted to f address sections with no consensus. This process is repeated until all opinions converge, resulting in the final consensus score.

According to the FDM, three representative indexes were selected for each aspect based on consensus scores above 6. The representative indexes for the "Necessity" aspect are land use, protection of residents, and emergency shelter. For the "Urgency" aspect, the selected indexes include wave overtopping discharge for a 50-year period, erosion rate, and beach width. Lastly, the "Feasibility" aspect includes regulations and policies, the cost ratio of maintenance to retreat, and land ownership. The coastal deterioration indexes and their corresponding meanings are shown in Table 1.

3.2 Grading the deterioration level

In order to quantify the likelihood or severity of coastal deterioration according to the representative indexes, the study systematically grades these indexes according to their characteristics through qualitative, quantitative, or semi-quantitative analyses into five levels, corresponding to scores of 1 to 5. The method of scoring each representative index is shown in Table 2. All indexes were treated equally as suggested by Cutter et al. (2000) and Boruff et al. (2005), because they all have the same relative importance and contribution to the designation of Deteriorated Areas.

The area described by the quantitative index scores is situated within a coastal protection zone. The main reason for this is that the legal basis for the designation of Deteriorated Areas is the Coastal Management Act, and the retreat strategy is one of the coastal protection strategies for the coastal protection zones. Each section of the coastline is assigned scores for each representative index. The coastal deterioration score is calculated as the square root of the product of the ranked indexes divided by the total number of indexes as in Eq. 1 below, which is similar to that used in USGS (Thieler and Hammar-Klose 2000; Pendleton et al. 2004).

$$\text{Coastal Deterioration Score} = \sqrt{(a * b * c * d * e * f * \dots)/n}$$

3

where n is the number of the representative indexes which is 9 in the present study, whereas a, b, c…are quantitative index scores.

These categories serve as a reference for evaluating the deterioration levels of various coastal sections, particularly those with coastal defense measures. This evaluation is crucial for prioritizing adaptation strategies, such as implementing retreat measures and restoring coastlines to their natural state.

The scale for each level of coastal deterioration is based on nine representative factors represented by deterioration indexes. All possible combinations of scores are calculated and normalized, after which these normalized deterioration scores are categorized into five levels of deterioration: I (Minor deterioration), II (Continuous deterioration), III (Significant deterioration), IV (Severe deterioration), and V (Extreme deterioration).

It is important to note that during the assessment of the coastal deterioration index, insufficient data or various other factors may hinder the evaluation of deterioration levels along shorelines with coastal defense measures. In such cases, these areas are classified under level N. To obtain the data necessary for assessing coastal deterioration in these sections, reviews should be systematically conducted through monitoring surveys and other programs.

This study focuses on coastal areas regulated by the Coastal Management Act. In Hualien, the landward boundary of coastal areas is defined by the coastal highway. Therefore, for the purpose of assessing and designating Deteriorated Areas, the landward boundary extends to the seaward edge of the coastal highway.

Depending on the degree of deterioration, different strategies should be adopted. For minor, continuous, and significant deterioration levels, the primary focus should be protection and adaptation. Conversely, areas experiencing severe and extreme deterioration, where the costs of ongoing investment in coastal defense facilities is no longer justifiable by their effectiveness should be designated as Deteriorated Areas. The grading scales and strategies corresponding to each deterioration level are shown in Table 3. The goal should be to gradually implement coastal setback measures in these locations.

Table 1
The meaning of each coastal deterioration index regarding necessity, urgency, and feasibility. The final column indicates the representative indexes selected.

Main aspects	Coastal deterioration indexes	Meaning	Selected
Necessity	Land use	Identify the status of land use behind coastal defense, such as houses, infrastructure, agriculture, and protected forests. The greater the intensity of land use, the lesser the necessity for designation as a Deteriorated Area.	□
	Protected residents	Calculate the number of protected residents. The more residents are protected, the lesser the necessity for designation as a Deteriorated Area.	□
	Population density	Calculate the population density of the urban planning area, rural area, industry, and public facility. The higher the population density, the lower the need for designation as a Deteriorated Area.	-
	Vulnerable populations	Calculate the number of residents under 14 years of age, over 65 years of age, and disabled. The more vulnerable residents there are, the lesser the necessity for designation as a Deteriorated Area.	-
	Economic industry	Determine whether there is industrial, science, creative, etc. parks or businesses with high capitalization (e.g., hotels). The higher the value of the economic industry, the lesser the necessity for designation as a Deteriorated Area.	-
	Emergency shelter	Determine the number and location of emergency shelters in the area. The more emergency shelters, the lesser the necessity for designation as a Deteriorated Area.	□
Urgency	Wave overtopping discharge for 50-year return period	Assess whether the wave overtopping discharge for a 50-year return period may damage coastal defences or threaten coastal residents' safety. The higher the wave overtopping discharge, the greater the urgency to designate Deteriorated Areas.	□
	Status of coastal defenses	Assess whether the coastal defenses are old, dilapidated, or sunken, or whether their functions and durability meet the original design criteria. The worse the status of the coastal defenses, the greater the urgency to designate Deteriorated Areas.	-
	Erosion rate	Estimate the change rate of the high tide lines over the last 5 years. The higher the erosion rate, the greater the urgency to designate Deteriorated Areas.	□
	Width of beach	Survey the width of the beach. The narrower the beach, the greater the urgency to designate Deteriorated Areas.	□

Main aspects	Coastal deterioration indexes	Meaning	Selected
	Historical disasters	Identify disaster-prone areas by studying historical disasters, such as typhoons and earthquakes, that caused damage to coastal defenses. The greater the number of historical disasters, the greater the urgency to designate Deteriorated Areas.	-
	Public complaints	Identify disaster-prone locations on the basis of public complaints and on-site surveys. The greater the number of public complaints, the greater the urgency to designate Deteriorated Areas.	-
	Sea level rise	Assess the impact of sea level rise on coastal defenses under climate change scenarios. The bigger the impact on coastal defenses, the greater the urgency to designate Deteriorated Areas.	-
	Wave overtopping discharge under climate change scenario	Determine whether waves overtopping coastal defenses under climate change scenarios will cause damage to the defenses or threaten the life and property of people within their hinterland. The bigger the impact on coastal defenses or coastal residential property, the greater the urgency to designate Deteriorated Areas.	-
	Coastal hazard risks	Identify coastal hazard risks to assess the impact of coastal hazards on the surroundings. The bigger the impact on coastal defenses or coastal residential property, the greater the urgency to designate Deteriorated Areas.	-
	Coastal protection area	Areas designated as protection areas are prone to hazards. It is also urgent to designate such areas as Deteriorated Areas.	-
Feasibility	Regulations and policies	Use overlay analysis to determine whether the area is designated as various statutory zones. The more times an area is designated as a statutory zone, the stricter the regulations become, and the more likely it is to be designated as a Deteriorated Area.	□
	Ecological reservation areas	Assess whether the area is situated within an ecological reservation zone. Ecological reservation areas are regions of significant importance to humans, often at risk from natural disasters, and are highly vulnerable to negative environmental impacts resulting from improper development activities. If an ecological reserve has been established, it is beneficial to designate it as a Deteriorated Area.	-
	Unauthorized or illegal use of land	Evaluate potential non-compliance or illegal land use in the area. If any violations are detected, the land use rights may be recovered in accordance with the law. If legally acquired, potentially hazardous areas can more easily be designated as Deteriorated Areas.	-

Main aspects	Coastal deterioration indexes	Meaning	Selected
	Relevant agencies	Identify all agencies that will be involved in the designation of Deteriorated Areas. The fewer the agencies involved, the easier it is to designate Deteriorated Areas.	-
	Cost ratio of maintenance to retreat	Compare the costs of maintaining coastal defenses and the cost of land acquisition and compensation for retreat. The larger the ratio, the more favorable the designation of the land as a Deteriorated Area.	□
	Land ownership	Land behind coastal defenses with relatively simple rights holders (e.g., state-owned land) should be prioritized.	□
	Public opinion	The feasibility of designating a Deteriorated Area depends on the level of agreement among the public.	-

Table 2
The assessment and scoring of each representative index regarding necessity, urgency, and feasibility.

Main Aspects		**Necessity**		
Representative indexes		Land use	Protected residents	Emergency shelters
Index level	Index score			
Low	1	Construction and public purposes	80% ≦ Percentile rank	distance to an emergency shelter < 500 meters
Low-intermediate	2	Recreation and transportation purposes	60% ≦ Percentile rank < 80%	500 meters ≦ distance to an emergency shelter < 1,000 meters
Moderate	3	Agricultural	40% ≦ Percentile rank < 60%	1,000 meters ≦ distance to an emergency shelter < 1,500 meters
High-intermediate	4	Salt production	20% ≦ Percentile rank < 40%	1,500 meters ≦ distance to an emergency shelter < 2,000 meters
High	5	Forest, water and other land use	20% < Percentile rank	2000 meters ≦ distance to an emergency shelter
Main aspects		Urgency		
Representative indexes		Erosion rate	Beach width	Wave overtopping discharge for a 50-year return period
Low	1	Erosion rate of the high tide line < 1 m/year	100m ≦ Beach width	75% ≦ Percentile rank of the freeboard
Low-intermediate	2	1 m/year ≦ Erosion rate of the high tide line < 2 m/year	75 m ≦ Beach width < 100 m	50% ≦ Percentile rank of the freeboard < 75%
Moderate	3	2 m/year ≦ Erosion rate of the high tide line < 3 m/year	50 m ≦ Beach width < 75m	25% ≦ Percentile rank of the freeboard < 50%
High-intermediate	4	3 m/year ≦ Erosion rate of the high tide line < 4 m/year	25 m ≦ Beach width < 50 m	Percentile rank of the freeboard < 25%
High	5	4 m/year ≦ Erosion rate of the high tide line	Beach width < 25 m	Not meet the Protection Code
Main aspects		Feasibility		
Representative indexes		Regulations and policies	Cost ratio of maintenance to	Land ownership

Main Aspects		Necessity		
			retreat	
Low	1	None of the related designated statutory areas overlaid	Ratio < 0.5	Percentage of state-owned land < 20%
Low-intermediate	2	One related designated statutory area	0.5 ≦ Ratio < 1	20% ≦ Percentage of state-owned land < 40%
Moderate	3	Two related designated statutory area	1 ≦ Ratio < 1.5	40% ≦ Percentage of state-owned land < 60%
High-intermediate	4	Three related designated statutory area	1.5 ≦ Ratio < 2	60% ≦ Percentage of state-owned land < 80%
High	5	Four related designated statutory area	2 ≦ Ratio	80% ≦ Percentage of state-owned land

Table 3
The classification of deterioration levels, along with the corresponding scores and strategies.

Deterioration level	Normalized deterioration scores	Adaption strategy
I (Minor deterioration)	0.00 ~ 1.88	Protection, accommodation
II (Continuous deterioration)	1.89 ~ 5.63	
III (Significant deterioration)	5.64 ~ 12.11	
IV (Severe deterioration)	12.12 ~ 23.52	Mid term: protection, accommodation
V (Extreme deterioration)	23.53 ~ 100.00	Long term: retreat
N (Impossible to judge)	Insufficient data or other reasons	Protection, accommodation

4. Results

This study analyzed the "necessity," "urgency," and "feasibility" of designating Deteriorated Areas by using representative indexes for different coastal sectors protected by coastal defenses. Each index was quantified based on a grading method established in this study. Finally, the degree of deterioration of the coastal sectors was determined using the estimated deterioration levels to assess the need for maintenance of the coastal defenses. To illustrate the process, the present study identifies the level of one representative index for each of the three main aspects of analysis.

4.1 Determining the levels and scores for representative indexes

4.1.1 Necessity

The representative indexes of necessity identified in this study are land use, protected residents, and emergency shelters. The one selected for discussion is land use. The data were acquired from the official unit, National Land Surveying and Mapping Center, Ministry of Interior, Taiwan. Land use investigation was preceded by digitizing the area of current land use showing up in aerial and remote-sensing imagery. Field investigations and records were also used to establish the current category of land use. The results of land use investigation provide an important reference for socio-economic development and land use planning. The investigation of land use map covered 9 major categories: agriculture, forests, transportation, water, construction, public facilities, recreation, mining/salt production, and others. The scores corresponding to each category are presented in Table 2. The land use categories of forest, water, and other land use are classified as “high” in terms of potential to implement the retreat strategy. Figure 3 shows the percentage of area in different land use behind the protective facilities. Accordingly, the index level is “high” for five of the protected coastal sectors, “moderate” for ten, and “low” for the rest.

4.1.2 Urgency

As far as urgency is concerned, the representative indexes are erosion rate, beach width, and wave overtopping discharge. The analysis of changes in the high tide line is a major approach used to classify erosional coast sectors into vertical control sections of the shoreline at an interval of 500 m. The change rate of high tide lines was calculated at two different points in time (in 2019 and 2024). Positive change rates indicate coastal accretion, whereas negative change rates mean that the coastal sectors are under threat of erosion. Table 4 presents average change rates for each coastal sector with protective facilities. It should be noted that the rates of change in the high tide line for shoreline segments with the Da-Kung revetment and the Dong-Xing revetment were found to be close to zero. This is because there is no longer any beach in front of the protective facility, and the shoreline is controlled by the structure. Therefore, the level of the urgency index for these segments is “high”.

4.1.3 Feasibility

The representative indexes of feasibility comprise regulations and policies, cost ratio of maintenance to retreat, and land ownership. Retreating from coastal areas involves various aspects, including coordination among agencies and compensation for stakeholders. Since this is a medium- to long-term plan, the costs associated with maintaining coastal protection facilities, as well as the expenses for land acquisition and compensation for those affected by the retreat, are projected based on the necessary expenditures required by the authorities overseeing the project over the next 50 years. The retreat cost, the value of the protective assets, and the ratios of the former to the latter are shown in Table 4. It should

be noted that the table does not provide ratios for 5 coastal sectors. This is because there are no assets within the area considered, and the land is owned by the state. In contrast, there are 3 coastal sectors with ratios of more than 1. That is to say, the protection of these sectors is not cost-effective.

4.2 The grading of each coastal sector

After determining the levels and the corresponding scores of the representative indexes for each coastal section with protective facilities, this study used the coastal deterioration assessment formula (Eq. 1) to derive deterioration scores for each of these coastal sections, and then compared them with the deterioration grading scale (Table 3) to determine the deterioration level, which was used as a reference for the adaption strategy. The deterioration assessment results for the coastal protection facilities in Hualien are shown in Table 5.

The Da-Kung revetment (Level V), the Dong-Xing revetment (Level V), and the Yong-Feng revetment (Level IV) have reached a severe or extreme level of deterioration, and it is incompatible with the rational allocation of protective resources and sustainable coastal development to continue to maintain them or reinforce them to prevent coastal disasters. Therefore, the process of designating them as Deteriorated Areas should be initiated to avoid the risk of hazard by retreating or evacuating the area and gradually restoring the coast to its original state.

The deterioration level of the remaining coastal protection facilities ranges from minor (Level I) to significant (Level III), and there is no need to include them in the retreat strategy. With regard to the risk of coastal hazards, they can be controlled by protective and adaptive techniques, such as maintaining the functions of existing coastal protection facilities, strengthening the disaster warning system, and maintaining low-density land use. The resilience-based adaptation management strategies for each coastal defense, including protective, accommodation, and retreat measures, are summarized in Table 5.

The deterioration assessment also revealed that some of the shoreline sections of the existing coastal protection facilities in Hualien lacked historical bathymetric and topographic monitoring survey data, and therefore it was impossible to determine the potential for coastal erosion hazards and the degree of deterioration. These shoreline segments include the Hua-Nan revetment, the Yan-Liao revetment, the Ji-Qi revetment, the Li-De seawall, the Jing-Pu seawall, and the San-Fu Creek revetment, that is, a total of six coastal protection facilities.

Table 4
The change rate of the high tide line and the cost ratio of maintenance to retreat for each protected shoreline segment.

Coastal defences	Annual change rate of the high tide line (m/year)	Maintenance cost (thousand NT)	Retreat cost (thousand NT)	Cost ratio of maintenance /retreat
Chong-De revetment	−0.86	2,327	1,749	1.33
Xin-Cheng seawall	+ 1.49	6,985	220,776	0.03
Northern section of the Shun-An Seawall	+ 1.05	13,426	816,570	0.02
Southern section of the Shun-An Seawall	−2.36	18,875	National land	-
Qixingtan revetment	+ 0.28	32,796	National land	-
Qixingtan seawall	−0.53	34,065	2,854,637	0.01
Bei-Bin seawall	−0.51	253,438	434,029	0.58
Nan-Bin seawall	+ 2.21	298,795	14,062	21.25
Hua-Ren seawall	−0.42	249,125	368,259	0.68
Hua-Ren revetment	+ 0.35	18,882	647,411	0.03
Da-Kung revetment	-0.02	7,158	National land	-
Hua-Nan revetment	n/a-	53,061	178,097	0.30
Yang-Liao revetment	n/a	213,097	647,412	0.33
Ji-Qi revetment	n/a	12,317	264,317	0.05
Xin-She revetment (I)	+ 1.17	76,170	182,026	0.42
Xin-She revetment (II)	+ 0.69	33,541	65,346	0.51
Dong-Xing revetment	+ 0.01	36,212	National land	-
Yong-Feng revetment	−0.61	3,231	National land	-

Coastal defences	Annual change rate of the high tide line (m/year)	Maintenance cost (thousand NT)	Retreat cost (thousand NT)	Cost ratio of maintenance /retreat
Fong-Bin village seawall	+ 0.60	33,864	315,188	0.11
Li-De seawall	n/a	43,651	48,841	0.89
Jing-Pu seawall	n/a	6,010	57,209	0.11
San-Fu creek revetment	n/a	13,203	7,383	1.79

Table 5
The deterioration level of each protected shoreline segment and its corresponding resilience-based adaptation management strategy.

Deterioration Level	Coastal Defences	Resilience-based Adaptation Management Strategy		
		Protection (short-term)	**Accommodation (mid-term)**	**Retreat (long-term)**
Level I (Minor deterioration)	Chong-De revetment, Xin-Cheng seawall, Northern section of Shun-An seawall, Qixingtan seawall, Bei-Bin seawall, Hua-Ren seawall, Hua-Ren revetment	Common strategy: • Maintain the functionality of protective facilities to meet design criteria. • Establish databases for coastal monitoring surveys and reviews of protective facility performance. • Conduct coastal hazard risk assessment. Localization strategy: • Review and improve Hua-Ren Seawall configuration (coastal environment restoration). • Plan beach nourishment in the coastal sector of the Bei-Bin seawall.	• Maintain "low-density land use". • Maintain emergency shelters. • Raise public awareness of coastal hazard risks and educate on prevention and mitigation; install disaster warning signs. • Review and update the Coastal Hazard Risk Assessment and Climate Change Impact Studies. • Ensure the disaster warning system remains fully functional.	The areas do not meet the criteria for designation as Deteriorated Areas (continue review in the future).
Level II (Continuous deterioration)	Southern section of Shun-An seawall, Qixingtan revetment, Nan-Bin seawall, Xin-She revetment (I), Fong-Bin village seawall	Common strategy: • Maintain the functionality of protective facilities to meet design criteria. • Establish databases for coastal monitoring surveys and	• Raise public awareness of coastal hazard risks and educate on prevention and mitigation; install disaster warning signs. • Review and update the Coastal Hazard Risk Assessment and	The areas do not meet the criteria for designation as Deteriorated Areas (continue review in the future).

Deterioration Level	Coastal Defences	Resilience-based Adaptation Management Strategy		
		Protection (short-term)	**Accommodation (mid-term)**	**Retreat (long-term)**
		reviews of protective facility performance. • Conduct coastal hazard risk assessment. Localization strategy: • Investigate coastal cliff collapse mechanisms, conduct research on cliff toe protection, and develop strategies for erosion response and prevention. [Xin-She revetment (I)]	Climate Change Impact Studies. • Ensure the disaster warning system remains fully functional. • Reduce land use intensity in the region and, when necessary, propose proactive restoration plans. • Implement disaster prevention, response, and mitigation measures, along with restoration efforts. • Plan or maintain emergency shelters.	
Level III (Significant deterioration)	Xin-She revetment (II)	• Maintain the functionality of protective facilities to meet design criteria. • Establish databases for coastal monitoring surveys and reviews of protective facility performance. • Conduct coastal hazard risk assessment.	• Review and update the Coastal Hazard Risk Assessment, and evaluate the feasibility of designating Deteriorated Areas. • Reduce land development use in the region and propose proactive restoration plans. • Implement disaster prevention, response, and mitigation measures, along with restoration efforts.	
Level IV (Severe deterioration)	Yong-Feng revetment	• Maintain the functionality of protective facilities to meet design criteria.	• Avoid creating new areas for human development or	• Begin the process of designating Deteriorated Areas.

Deterioration Level	Coastal Defences	Resilience-based Adaptation Management Strategy		
		Protection (short-term)	Accommodation (mid-term)	Retreat (long-term)
		• Increase the frequency of coastal monitoring surveys and review the performance of protective facilities. • Renew the coastal hazard risk assessment on an annual basis.	expanding the existing ones. • Plan or maintain emergency shelters.	• Conduct consultative discussions and review meetings to identify these areas. • Before Deteriorated Areas have been designated, public land leases will not be renewed and will be terminated upon expiration. Additionally, state-owned land will be reclaimed for management and restoration purposes.
Level V (Extreme deterioration)	Da-Kung revetment, Dong-Xing revetment			
Level N (Impossible to judge)	Hua-Nan revetment, Yang-Liao revetment, Ji-Qi revetment, Li-De seawall, Jing-Pu seawall, San-Fu creek revetment	• Maintain the functionality of protective facilities to meet design criteria. • Prioritize coastal monitoring surveys and reviews of protective facility performance. • Conduct coastal hazard risk assessment.	• Review and update the Coastal Hazard Risk Assessment, and evaluate the feasibility of designating Deteriorated Areas. • Maintain "low-density land use". • Plan or maintain emergency shelters. • Raise public awareness of coastal hazard risks and educate on prevention and mitigation; install disaster warning signs.	Impossible to judge (continue review in the future).

5. Discussions

The designation of Deteriorated Areas aims to reduce land use intensity, implement land expropriation, or relocate residents when external hazards exceed the capacity of protective measures or when such measures are no longer cost-effective. The primary objective is to avoid or minimize potential losses. The practical implementation includes the following:

1. Once an area is designated as a Deteriorated Area, it indicates that continued protection is unnecessary or inefficient. Accordingly, the maintenance of existing protective facilities should be reduced or discontinued, and the associated resources should be withdrawn and reallocated to more suitable areas.
2. Development within Deteriorated Areas should be strictly regulated, following the principle of low-density land use. For public land, land-use intensity should be controlled. For educational, cultural, and public facilities, coordination with relevant authorities is required to relocate or reassign these functions to safer areas. Private land use should also be regulated, and where appropriate, land may be acquired through expropriation or land readjustment to enable integrated public management and planning.

The process also highlights the need for financial support to implement the measures. Consequently, local governments may face challenges related to budget constraints and potential financial losses. To address these issues and promote broader participation in coastal conservation efforts, the Coastal Management Act allows the competent authority to establish a Coastal Management Fund. This fund would provide subsidies for coastal conservation and restoration, as well as for coastal surveys and monitoring. In essence, the Coastal Management Fund is intended to strengthen the sustainability and integrity of overall coastal management by creating a comprehensive compensation mechanism for retreat from Deteriorated Areas.

In recent years, the Taiwan government has taken steps to address the threat of climate change, including initiatives aimed at halving greenhouse gas emissions and achieving net-zero carbon emissions. The Climate Change Response Act, which came into effect in 2023, aims to reach net-zero emissions by 2050. This will be accomplished through the establishment of specific powers and responsibilities for various ministries, along with the implementation of a carbon levy for designated purposes.

To facilitate this process, the Taiwan Stock Exchange and the National Development Fund Administration have jointly created the Taiwan Carbon Rights Exchange. This platform is designed to effectively balance supply and demand, incentivize companies to reduce carbon emissions, and promote the development of low-carbon production technologies and innovative industries.

Moreover, large international corporations are responding to net-zero emissions initiatives by urging their suppliers to implement relevant carbon reduction strategies as part of their corporate social responsibility (CSR) efforts.

Carbon credits, carbon taxes, carbon fees, carbon neutrality, and similar policies aimed at achieving net-zero greenhouse gas emissions are not just national development goals; they are also challenges that local industries and international enterprises have been facing in recent years. These entities must find effective solutions to address these issues.

This study suggests that a strategy focused on "natural carbon sinks" can be integrated with the studies and management of carbon sinks in forests, soils, and coastal areas, especially in Deteriorated Areas, to enhance the effectiveness of blue carbon sinks. In promoting initiatives such as land retreat, returning land to the sea, and restoring coasts to their natural state, it is important to consider the potential of carbon sinks.

Private enterprises are encouraged to engage in Corporate Social Responsibility (CSR) initiatives by adopting projects and making donations. One effective way to do this is by restoring coastal areas to their natural state. In return for their efforts, companies can earn carbon credits, providing a strong incentive for their involvement.

6. Conclusions

This study emphasizes the need for sustainable coastal management in Taiwan, particularly in hazard-prone areas, such as the Hualien coast. It advocates for a shift from traditional protection focused methods to strategies based on scientific understanding that incorporate hazard assessment, land use planning, and socioeconomic considerations. With increasing coastal risks driven by climate change, declining populations in scattered settlements, and rising maintenance costs of coastal defenses, relying on hard protections in every coastal area is neither economically feasible nor environmentally sustainable.

To address this issue, the study proposes a structured framework for identifying Deteriorated Areas. For that purpose, it uses representative indexes chosen through the FDM, which are categorized into three aspects: necessity, urgency, and feasibility. Each coastal sector is evaluated based on a coastal deterioration score derived from a geometric mean scoring system. The findings reveal which sectors have manageable hazard levels, where it is appropriate to maintain existing protections and adaptive measures, and which sectors are undergoing severe or extreme deterioration, where further investment in coastal defenses is unjustifiable. For these Deteriorated Areas, retreat strategies and setback zoning should be implemented to mitigate long term risks, restore ecological functions, and promote sustainable development.

Effective setback planning requires reliable hazard data, economic and legal feasibility, stakeholder engagement, and clear communication with affected communities. Setback policies that do not consider social acceptance and economic factors may remain theoretical. This study offers a practical decision support tool to help coastal managers determine where coastal defenses should be maintained, strengthened, or removed, ultimately facilitating risk informed retreat and enhancing long-term coastal resilience.

The designation of Deteriorated Areas underscores the need for financial support to implement retreat and adaptation measures. The Coastal Management Fund provides a mechanism to support conservation and restoration efforts while addressing budget constraints. In the context of Taiwan’s net-zero emission goals, integrating coastal management with blue carbon strategies offers additional

benefits. Promoting nature-based solutions and encouraging private sector participation through carbon credit mechanisms can enhance both coastal resilience and environmental sustainability.

Declarations

Conflict of interest

The authors declare that they have no competing interests.

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Author Contribution

Conceptualization, W.-P.H. and C.-J.Y.; formal analysis, W.-P.H., C.-J.Y., and J.-C.H.; methodology, W.-P.H. and C.-J.Y.; resources, W.-P.H.; software, C.-J.Y. and J.-C.H.; supervision, W.-P.H.; visualization, W.-P.H. and C.-J.Y.; writing—original draft, W.-P.H., C.-J.Y. and P. S; writing—review and editing, W.-P.H., C.-J.Y. and P. S. All authors have read and agreed to the published version of the manuscript.

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Figures



Figure 1

Geographic locations and scenes of each coastal protection facility.

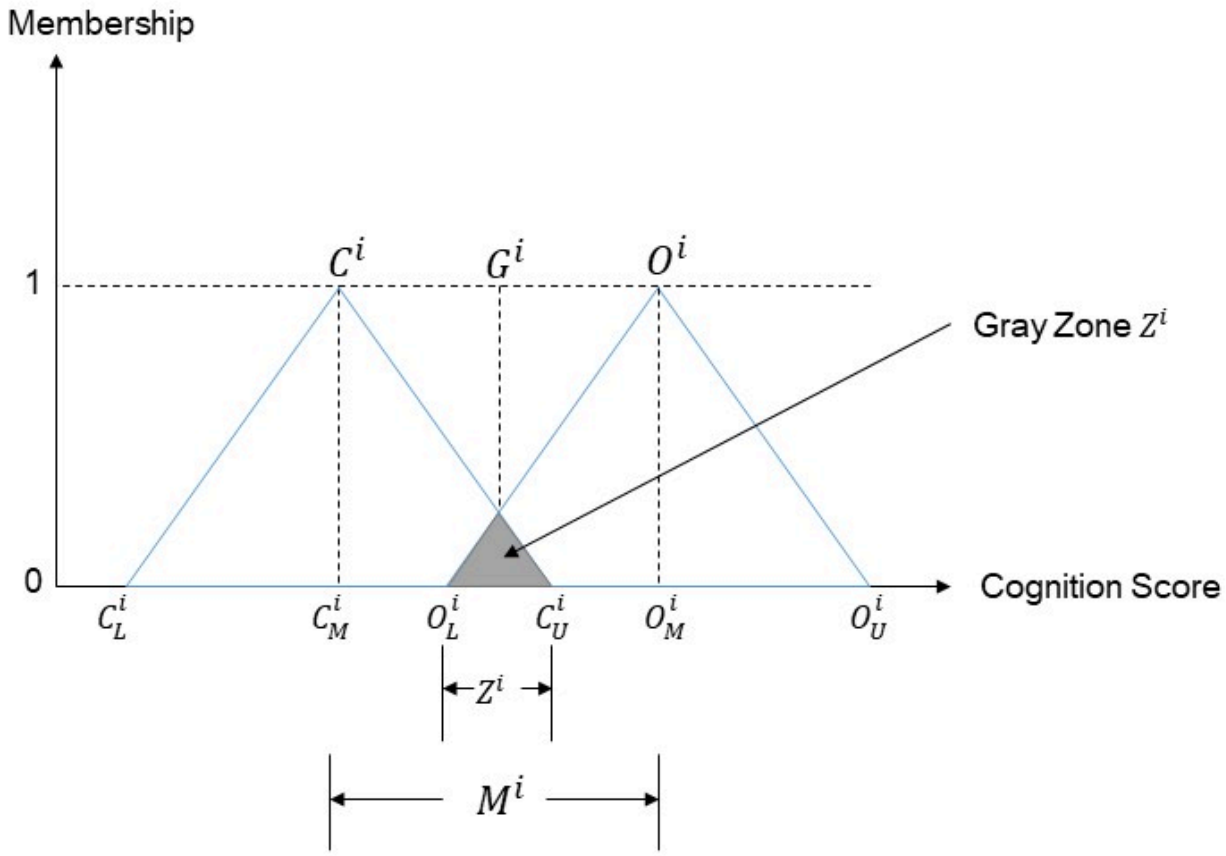


Figure 2

Triangular fuzzy numbers and gray zone test formed using the fuzzy Delphi method (FDM).



Figure 3

The percentage of area in different land use behind each protective facility.

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