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## Assessing the vulnerability of marine ecosystems in the Gulf of Tonkin to human impacts and climate change - natural disasters

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### ABSTRACT

The Gulf of Tonkin (Vietnam part) comprises 12 typical marine ecosystems distributed in 7 ecological regions. Human activities impacting the marine ecosystems are classified into three groups: strong impacts (fishing, aquaculture, navigation - ports, and marine infilling); medium impacts (dredging - dumping, mining, tourism - services); and weak impacts (security - defense). Climate change and natural disasters affecting marine ecosystems are categorized into three impact groups. The strong impact group includes water temperature, typhoons, waves, and rising sea levels. The medium impact group consists of turbidization, local freshening, salinization, and erosion. The low impact group comprises circulation disturbances and sedimentation. The vulnerability of the marine ecosystems, influenced by human activities and climate change - natural disasters, varies and is classified into three levels. High vulnerability includes lagoons, estuarine areas, tidal flats, seagrass beds, and coral reefs. The medium vulnerability encompasses ecosystems such as beaches, mangrove forests, and permanent wetlands. The low vulnerability comprises ecosystems such as the sea bottom, marine lakes, rocky coasts, and upwelling areas. Ecological zones with a high vulnerability levels include the coastal marine zones of Mong Cai - Do Son (Z.1) and Mui Roon - Hai Van (Z.4). The zones with medium vulnerability levels include the coastal marine zones of Do Son - Lach Truong (Z.2) and Lach Truong - Mui Roon (Z.3). In contrast zones with a low vulnerability levels include the northern marine zones of the Gulf (Z.5), the middle marine zone of the Gulf (Z.6), and the southern marine zone of the Gulf (Z.7).

**Keywords:** Marine ecosystems, Gulf of Tonkin, vulnerability, human activities, climate change.

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## Introduction

The Gulf of Tonkin is located between coordinates 17°00' to 21°04'N and 105°04' to 109°04'E. Its natural boundary is defined by a closing line that connects the Sanya Cape in China to the Hai Van Cape in Vietnam. Situated in the northwest of the East Vietnam Sea, this relatively enclosed gulf is one of the shallow, gentle, and wide continental shelves globally. It occupies an area of about 150,000 km<sup>2</sup>, of which the gulf part of Vietnam is about 80,000 km<sup>2</sup>. The West Coast of the Gulf stretches across 11 provinces and cities, from Quang Ninh Province to Thua Thien-Hue Province, in the North and North Central regions of Vietnam.

Vietnam's part of the Gulf encompasses 7 ecological zones within 2 natural-ecological regions, hosting 12 typical ecosystems. These include estuarine areas, lagoons, mangrove forests, coral reefs, seagrass beds, beaches, tidal flats, rocky coasts, permanent wetlands, marine lakes, sea bottoms, and upwelling areas. The Gulf is highly valued for nature conservation and biodiversity. Sixteen marine protected areas have been planned by 2030, including 4 marine national parks, 10 marine natural reserve areas, and 2 marine landscape protection areas.

The Gulf of Tonkin possesses abundant natural resources, particularly in fisheries, petroleum, mineral deposits, and positional resources. Recent years have witnessed robust socio-economic development along its coastal regions, seas, and islands. This development includes the expansion of urbanization areas, economic zones, industrial parks, and transport and port infrastructure enhancements. Additionally, the region has seen growth in the tourism and service industries, alongside flourishing fishing and aquaculture activities.

The Gulf of Tonkin is susceptible to various natural disasters, including typhoons, coastal erosion, sedimentation, and coastal flooding. Additionally, it faces significant potential impacts from climate change and rising sea levels. The unsustainable exploitation and utilization of natural resources have led to environmental degradation and harm to the marine ecosystems. This article aims to present

the findings of assessing the vulnerability of the marine ecosystems in the Gulf of Tonkin to human activities and climate change-induced natural disasters. Such assessments provide crucial groundwork for the establishment and implementation of ecosystem-based marine spatial planning [1] and integrated coastal zone management [2].

## Materials and methods

### Materials

The materials originate from the state project with code KC.09.16/16-20<sup>1</sup>: "Research and development of a marine spatial planning plan in the Gulf of Tonkin". Additionally, this article utilizes existing the research results on marine ecosystems in general<sup>2</sup> [3, 4], and specific studies on individual ecosystems such as coral reefs [5, 6], seagrass beds [7, 8], mangrove forests [9–11], lagoons [12, 13], estuarine areas [14], tidal flats<sup>3</sup> [3], marine lakes [15], and upwelling areas [16]. The assessment of current climate conditions and future projections is derived on the scenarios outlined by the Ministry of Natural Resources and Environment for 2021 [17], along with other studies on the climate change impacts [18–20]

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<sup>1</sup>Tran Duc Thanh (editor), 2020. Research on developing a marine spatial planning plan in the Gulf of Tonkin. State-level project report, code KC.09.16/16–20, archived at the Institute of Marine Natural Resources and Environment, Hai Phong.

<sup>2</sup>Nguyen Huy Yet (editor) et al., 2010. Assessing the level of degradation of Vietnam's coastal ecosystems and proposing sustainable management solutions. State-level project report, code KC.09-26/06–10, archived at the Institute of Marine Natural Resources and Environment, Hai Phong.

<sup>3</sup>Do Cong Thung (editor), 2016. Research on the current state of the environment, changes in resources, and biodiversity of the tidal ecosystem in coastal zone of Northern Vietnam, proposing a model for exploitation and aquaculture, conservation and sustainable management. State-level project report, code KC09.07/11–15, archived at the Institute of Marine Natural Resources and Environment, Hai Phong.

and their impacts on the environment and ecosystems [21–23].

### **Methods**

The DPSIR framework analysis method was used. Here, the driver represents the climate change [24] and human activities [25], Pressure includes impact factors related to human activities and climate change - natural disasters; State is the health status of ecosystems and the perceived effects of human activities and climate change - natural disasters; Impact denote the level of influence corresponding to the average climate change scenario [17]; Response here is interpreted as priority options to protect ecosystems and ecological zones in marine spatial planning.

Establishing a matrix and scoring weights [26] is used to analyze and evaluate the impact of human activities, climate change, and natural disasters on the ecosystems and ecological zones in the Gulf of Tonkin.

The human activities include 8 factors selected for evaluation, including fishing, aquaculture, navigation - ports, marine infilling, dredging and dumping, mining, tourism and services, security, and defense. Nine factors related to climate change and natural disasters were chosen for evaluation. These factors include rising water temperatures, typhoons, waves, sea-level rise, and turbidization. Other factors evaluated are local freshening, salinization, erosion, circulation disturbances, and sedimentation.

The Gulf of Tonkin has 12 typical marine ecosystems selected to assess the level of impact, including estuarine areas, lagoons, tidal flats, mangrove forests, seagrass beds, coral reefs, marine lakes, beaches, rocky coasts, permanent wetlands, sea bottom, and upwelling areas. They are distributed in different marine ecological zones. In the impact-affected relationship matrix, we can see the influence of each factor affecting each ecosystem.

A weighted score of 0 indicates a negligible or no impact: stable ecosystem health. A weighted score 1 represents the weak impact level: ecosystem health is little affected, but it

can adapt, withstand and recover if there are no additional negative impacts from human activities or climate change - natural disasters. A weighted score 2 signifies moderate impact: ecosystem health is significantly affected, demonstrates a poor ability to adapt, resist, and recover, and is susceptible to degradation if there are additional negative impacts from human activities or climate change - natural disasters. A weighted score 3 denotes strong impact: ecosystem health is seriously affected, shows a very poor ability to adapt, withstand, and recover, and can be degraded, even destroyed, if there are no solutions to protect and respond actively.

### **Results and discussion**

#### ***Distribution of marine ecosystems in the Gulf of Tonkin (Vietnam part)***

Based on the topographical, geological, climatic, and hydrological characteristics, and marine ecosystems, Vietnam's part of the Gulf of Tonkin is divided into seven ecological zones (Table 1, Fig. 1). The coastal marine zones Z.1, Z.2, and Z.3 extend from the coastline to approximately 30 m, with zone Z.4 reaching depths of around 50 m. The marine zones Z.5 and Z.6 are situated beyond the coastal marine region at depths of about 30 m, while the marine zone Z.7 is located further offshore at depths of approximately 50 m.

Ecological zones: Z.1- coastal marine zone of Mong Cai - Do Son; Z.2- coastal marine zone of Do Son - Lach Truong; Z.3 - coastal marine zone of Lach Truong - Mui Ron; Z.4 - coastal marine zone of Mui Ron - Hai Van; Z.5 - northern marine zone of the Gulf; Z.6 - middle marine zone of the Gulf; Z.7 - southern marine zone of the Gulf.

The coastal marine zone from Mong Cai to Do Son (Z.1) hosts 10 marine ecosystems, including coral reefs, tidal flats, mangrove forests, marine lakes, and permanent wetlands. The Do Son - Lach Truong coastal area (Z.2) supports 7 marine ecosystems featuring tidal flats, estuarine areas, mangrove forests, and permanent wetlands. From Lach Truong - Mui

Ron (Z.3), there occur 9 marine ecosystems, with beaches, estuarine areas, and permanent wetlands as notable features. From Mui Ron - Hai Van (Z.4), 10 marine ecosystems are found, with lagoons, beaches, seagrass beds, and permanent wetlands being prominent. In the Gulf's northern marine zone (Z.5), 06 typical marine ecosystems exist, including the upwelling area that develops during the northeast monsoon season. The Bach Long Vi island, located in this zone, contains ecosystems such as coral reefs, beaches, rocky coasts, and permanent wetlands. The middle marine zone of the Gulf (Z.6) is distinguished by two typical ecosystems, with the upwelling ecosystem forming near the Vinh - Ha Tinh coast during the southwest monsoon season. Finally, The south marine zone of the Gulf (Z.7) is defined by a sea bottom ecosystem, incorporating the commonly soft sea bottom sub-ecosystem and the limited submerged hill sub-ecosystem.

*The estuarine ecosystem* in the Gulf of Tonkin is distinguished by densely spaced river mouths along the northern coast (32 river mouths per 515 km) and less frequent occurrences along the north-central coast (24 river mouths per 642 km).

The Red River system (Fig. 2a), ranked 14<sup>th</sup> globally, 5<sup>th</sup> in East Asia, and second in Vietnam, contributes significantly to this ecosystem. The Bach Dang Estuarine Area represents a typical funnel-shaped estuary and the second largest in Vietnam. These estuaries sustain rich and diverse biological communities, comprising brackish, freshwater, and saltwater species. Boasting high biological productivity and species diversity, estuarine areas provide considerable fishing and aquaculture resources [14]. The coastal waters near the estuarine areas host many essential fishing grounds for fish and shrimp.

*The lagoon ecosystem* is distributed in zone Z.4, including the Tam Giang - Cau Hai Lagoon with an area of 216 km<sup>2</sup>, the largest lagoon in Vietnam, and the Lang Co lagoon (Fig. 2b) with an area of 16 km<sup>2</sup>. The area features a wide variety of habitats, including estuaries, marshes, seagrass beds, and muddy or sandy bottoms. This diversity of habitats supports high biodiversity, home to 921 aquatic species and 73 bird species. Spawning grounds and larval growth areas are formed in the lagoons, providing seed sources for the lagoons and the outer marine areas [27].

Table 1. Distribution of typical marine ecosystems in the Gulf of Tonkin

No.	Ecosystems	Z.1	Z.2	Z.3	Z.4	Z.5	Z.6	Z.7
1	Estuarine area	+	x	+	-	0	0	0
2	Lagoon	0	0	0	x	0	0	0
3	Tidal flat	x	x	+	-	0	0	0
4	Mangrove	x	x	+	-	0	0	0
5	Seagrass bed	+	-	-	x		0	0
6	Coral reef	x	0	+	+	-	0	0
7	Marine lake	x	0	0	0	0	0	0
8	Beach	+	-	x	x	-	0	0
9	Rocky coast	+	0	-	-	-	0	0
10	Permanent wetlands	x	x	x	x	-	0	0
11	Sea bottom	+	+	+	+	x	x	x
12	Upwelling area	0	0	0	0	x	+	0
Total		10	7	9	10	6	2	1

Note: Distribution level: x is common; + relatively common; - less common; 0 none.

*The tidal flats ecosystem* covers about 60,115 hectares in area, including 38,204 hectares in Hai Phong - Quang Ninh, 18,826 ha in the Red River Delta, and 3085 ha in Thanh Hoa - Quang Tri [28]. Large tidal flats are concentrated in

Quang Ninh, Hai Phong, and Thai Binh (Fig. 2c), etc., where there are many exceptional seafood grounds. The species group that settles on the tidal flats includes about 150 species of benthic animals, 58 species of seaweed, 5 species of

seagrass, and 5 species of marine fish. The species living in the water layer that migrate according to tidal fluctuations include 145 species of phytoplankton, 54 species of

zooplankton and 74 species of marine fish. In addition, a few vertebrate animals, such as water snakes and birds, live and feed on the tidal flats during the ebb tide.

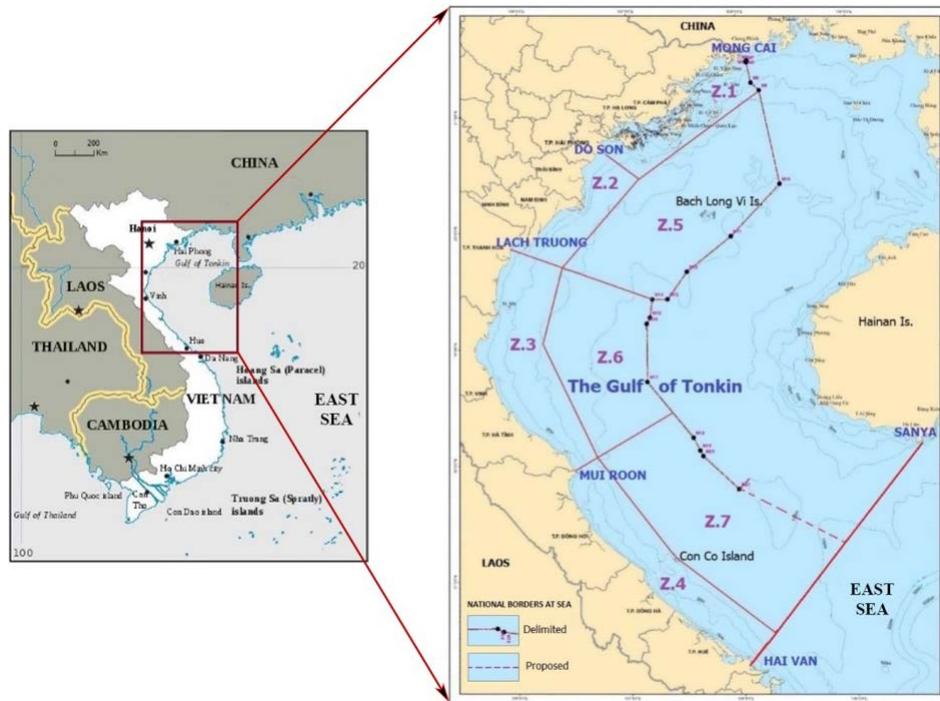


Figure 1. The ecological zones in the Gulf of Tonkin (Vietnam part): Z.1- coastal marine zone of Mong Cai - Do Son; Z.2 - coastal marine zone of Do Son - Lach Truong; Z.3 - coastal marine zone of Lach Truong - Mui Roon; Z.4 - coastal marine zone of Mui Roon - Hai Van; Z.5 - northern marine zone of the Gulf; Z.6 - middle marine zone of the Gulf; Z.7 - southern marine zone of the Gulf

The mangrove ecosystem in the western coastal zone of the Gulf of Tonkin (Fig. 2d) is divided into 4 zones [9], previously very widely distributed, now only about 32,000 ha, accounting for about 20% of the country's mangrove forest area. Along the Gulf coast, there are about 40 mangrove species, of which 35 species are distributed in the Mong Cai - Do Son zone, 24 species are from Do Son - Cua Tung [29]. Recent statistics have shown that mangroves in the Gulf have about 60 species, of which there are about 16 valid species, and 44 participating and migratory inland species [11].

The seagrass bed ecosystem on the western coast of the Gulf is known to support five distinct species of seagrass. Previously, seagrass beds (Fig. 2e) were common, but now their distribution has decreased much [7]. The

total area from Quang Ninh to Quang Binh is only about 2,8858 ha, often concentrated in coastal bays, estuarine areas, and brackish lagoons [8].

The coral reef ecosystem is relatively common around rocky islands (Fig. 2f) where salinity is stable and seawater is clear. Corals of the Gulf of Tonkin have a relatively affluent and diverse species composition [5, 6]. There are about 186 species belonging to 57 genera and 14 families of the hard coral order *Scleractinia*; the coverage is medium, average about 20.2%. The coral reef ecosystem has excellent value in storing genetic and biological resources of the Gulf of Tonkin waters [30].

The marine lake ecosystem, locally known as 'Ang' for isometric shapes and 'Tung' for elongated shapes, is distributed mainly in the

coastal areas of Quang Ninh - Hai Phong (Fig. 2g). They originate from karstic dolines or valleys submerged by sea water [31]. There are about 70 isometric marine lakes, 1–8 m deep, with an area of 0.1 ha or more, the largest being Ang Vem, with 23.2 ha. There

are about 57 elongated saltwater lakes, the largest being Tung Gau, with 220 ha, and the smallest is the Tung May Den, with 1.5 hectares. The marine lake ecosystem has quite a biodiversity, with many economically valuable and rare species [15].



Figure 2. Some typical marine ecosystems in the Gulf of Tonkin: a - Ba Lat estuarine area (Red River); b - Lang Co Lagoon (Thua Thien Hue Province); c - tidal flat in Dong Chau (Thai Binh Province); d - mangrove forest in Hoang Tan (Quang Ninh Province); e - seagrass bed (*Halophila ovalis*) in Tam Giang (Thua Thien Hue Province); f - coral reef in Bach Long Vi island (Hai Phong City); g - Ang Tham marine lake (Cat Ba, Hai Phong City); h - Sam Son Beach (Thanh Hoa Province); i - rocky coast in Do Son (Hai Phong City). Photo sources: Tran Duc Thanh (a-b, d, f-i), Nguyen Thanh Son (c, h), and Nguyen Van Tien (e)

The beach ecosystem, comprising hundreds of beaches on the mainland coast and Gulf of Tonkin islands (Fig. 2h), is formed by the accretion of sand, grit, gravel, or pebble sediments. They have a width of a few dozen to a few hundred meters and can be over a dozen kilometers long, like the Tra Co and Lang Co beaches. From Quang Ninh to Quang Tri, the area of beaches is about 6,637 ha. Although

the species composition is poor compared to other ecosystems, this is an extraordinary ecosystem where sea turtles lay their eggs [32].

The rocky coast ecosystem usually covers a small area, most commonly distributed in coastal marine zone Z.1 (Fig. 2i) along the islands of Bai Tu Long and Ha Long Bay. It is more limited in zones Z.3 and Z.4 [3]. From

Quang Ninh to Quang Tri, the rocky coast occupies approximately 1,162 ha.

*The ecosystem of permanent wetlands is common in coastal marine zones Z.1, Z.2, Z.3 and Z.4, and it is distributed from the shore to a depth of 6 m. The area is very large but has yet to be accurately counted; it is estimated to be about 395,682 ha from Quang Ninh to Quang Tri.*

*The sea bottom ecosystem includes sub-systems such as the soft sea bottom, hard sea bottom, and submerged hills [33], with seabed depths ranging from 6m to over a hundred meters. Coastal bays can be considered a particular sub-system because they are located close to the shore, the depth is not great, and the water body has a certain degree of closure. The Gulf of Tonkin has 12 coastal bays, with a total area of 1,970 km<sup>2</sup>, accounting for 49.2% of Vietnam's total coastal bay area [34].*

*The upwelling ecosystem appears in marine zone Z.5 during the Northeast monsoon season and in marine zone Z.6 during the Southwest monsoon season [16]. These are fishing grounds with a high exploitation output. Due to climate change, this ecosystem is strongly affected by increased water temperature, surface water salinization, and circulation disturbance; often in hot, dry years with little rain, the fishery output in upwelling areas.*

### ***Vulnerability of marine ecosystems and marine ecological zones in the Gulf of Tonkin due to human activities***

#### *Factors causing damage*

*Overfishing, mainly focusing exploitation in coastal areas, has resulted in a loss of biodiversity, a decline in seed sources, and the depletion of biological resources in the marine ecosystems [35]. Fishing on coral reefs and seagrass beds impairs and deteriorates the habitat in these fragile ecosystems. The employment of destructive fishing methods, such as explosives, chemicals (cyanide), electric pulses, excessive light, etc., triggers the mass death of aquatic organisms and the direct destruction of their habitat. Fishing activities and fishing services also contribute to oil pollution, organic waste, and solid waste, especially in fishing villages.*

*Over-aquaculture has reduced coastal ecosystems with high biodiversity, such as mangroves [36], tidal flats, and seagrass beds. In bays, lagoons, and estuarine areas it limits water circulation and reduces water exchange. Aquaculture waste due to excess food leads to pollution, sometimes at very high levels, affecting local and neighboring marine ecosystems.*

*Navigation and port infrastructure construction has significantly encroached upon coastal ecosystems, including permanent wetlands, tidal flats, beaches, mangrove forests, and seagrass beds. If not well managed, the Gulf of Tonkin and port waters on the gulf will suffer a deterioration of environmental quality [37], even severe pollution of oil, heavy metals [38], and toxic chemicals which have local and cross-border sources [39]. Oil and chemical spills can cause environmental disasters at sea [40]. In addition, ship activities at sea discharge solid waste, including plastic waste, and cause turbidization and noise pollution.*

*The marine infilling, which originally served agriculture and aquaculture, has recently shifted toward leveling the sea for the development of industrial zones and urban areas. The urbanization and development of coastal economic and service zones [41] have encroached on significant coastal ecosystem areas such as mangrove forests, tidal flats, beaches, and parliament flooded wetlands. In addition, these activities also change the shape of the shore and coastal circulation and cause turbidization, sedimentation, and the shallowing of the sea bottom of coastal water bodies.*

*Dredging and dumping for seaport and fishing wharf channels cause seabed disturbances and turbid pollution in the bottom ecosystems and permanent wetlands. Dredging also stirs the sediment layer, leading to the release of trapped pollutants into the water column. Furthermore, marine waste dumping activities originate from various sources and take multiple forms, further impacting the environment. Pollutants have been discharged from dredged sludge, ship ballast water, treated, and even untreated wastewater from coastal economic and industrial zones (typically pollution case from the Formosa factory in*

2016). Currently, plastic waste is a worrying problem for marine ecosystems.

*Mining activities* in the Gulf of Tonkin have recently focused on coastal areas, primarily targeting the extraction of coal, construction materials, and placer deposits. In the future, oil and gas exploitation may become a reality in the Gulf. Mining creates turbidization, heavy metals, oil, and other pollutants, and solid mine waste encroaches on coastal space. The mining of placers and construction materials such as sand and gravel can cause coastal erosion and damage beach ecosystems and coastal wetlands.

*Tourism and services* are forms of economic activity that cause little damage to marine ecosystems [35]. However, their impacts are diverse and can accumulate over time. Solid waste pollution, the biodiversity loss due to the demand for food and souvenirs, and the destruction of habitat due to tourist boat activities, etc., are regular impacts that need to be controlled.

*Security and defense activities*, while often having only small-scale impacts, can damage

the marine ecosystems when the construction of specialized defense works is prioritized.

*Vulnerability of marine ecosystems due to human activities*

The analysis of the relationship matrix between 8 human activity factors and 12 impacted ecosystems is summarized in Table 2. According to the level of impact, factors inducing vulnerability are divided into three groups: strong, medium, and weak. The group of factors causing intense vulnerability (weighted score for each factor > 20) comprises fishing, aquaculture, navigation-port, and sea leveling. The group of factors resulting in moderate vulnerability (weighted score for each factor ranges from 15–20) includes dredging and dumping, mineral exploitation, tourism, and services. The group of factors exerting weak vulnerability (weighted score for each factor < 15) consists of security - national defense. In Table 2, the level of damage caused by the factors is shown to decrease from left to right.

Table 2. Vulnerability Weighted matrix of marine ecosystems in the Gulf of Tonkin due to human activities

No.	Ecosystems	Activities								Total
		i	ii	iii	iv	v	vi	vii	viii	
1	Estuarine area	3	3	3	3	3	3	2	1	21
2	Lagoon	3	3	2	2	2	3	3	1	19
3	Tidal flats	3	3	2	3	3	1	2	1	18
4	Permanent wetlands	3	3	2	2	3	2	1	1	17
5	Coral reef	3	1	3	0	3	2	3	1	16
6	Seagrass bed	3	3	2	2	1	2	1	1	15
7	Mangrove forest	2	3	2	3	1	1	1	1	14
8	Beach	0	1	1	3	1	3	3	1	13
9	Sea bottom	3	1	2	0	2	1	0	1	10
10	Rocky coast	2	1	1	3	0	0	1	1	9
11	Marine lake	3	1	1	0	0	0	1	1	7
12	Upwelling area	3	0	1	0	0	0	0	1	5
Total		31	23	22	21	19	18	18	12	164

Notes: i- fishing; ii- aquaculture; iii- navigation-port; iv- marine infilling; v- dredging and dumping; vi- mining; vii- tourism and services; viii- security-defense.

According to the level of vulnerability resulting from human activities, the ecosystems are categorized into three vulnerability groups: high, medium, and low. The highly vulnerable ecosystems (total vulnerability score of each

ecosystem > 15) comprise estuarine areas, lagoons, tidal flats, permanent wetlands, and coral reefs. The group of ecosystems considered moderately vulnerable (the total vulnerability score of each ecosystem ranges from 11 to 15)

includes seagrass beds, mangrove forests, and beaches. The ecosystems exhibiting low vulnerability (total vulnerability weight score of each ecosystem < 11) consist of the sea bottom,

rocky coasts, marine lakes, and upwelling areas. In Table 2, from the top to the sea bottom, the order of decreasing vulnerability of the ecosystems due to human activities is presented.

Table 3. Vulnerability weighted matrix of ecosystems and ecological zones in the Gulf of Tonkin due to human activities

No.	Ecosystems	Ecological zones							Total
		Z.1	Z.4	Z.2	Z.3	Z.5	Z.6	Z.7	
1	Estuarine areas	4	2	10	5	0	0	0	21
2	Lagoons	0	19	0	0	0	0	0	19
3	Tidal flats	8	1	7	2	0	0	0	18
4	Permanent wetlands	5	3	4	4	1	0	0	17
5	Coral reefs	6	5	0	4	1	0	0	16
6	Seagrass bed	5	6	2	2	0	0	0	15
7	Mangrove forests	6	1	5	2	0	0	0	14
8	Beaches	2	5	1	4	1	0	0	13
9	Sea bottom	1	1	1	1	2	2	2	10
10	Rocky coasts	5	1	0	2	1	0	0	9
11	Marine lake	7	0	0	0	0	0	0	7
12	Upwelling area	0	0	0	0	3	2	0	5
Total		49	44	30	26	9	4	2	164

The waters of the Gulf of Tonkin (Vietnam part) include 7 different ecological zones. Each zone includes different typical ecosystems, and each ecosystem’s vulnerability level due to human activities has been determined (Table 2). From there, the level of vulnerability of the ecological zones and their matrix relationship with the level of vulnerability of each ecosystem present in each zone have been determined (Table 3).

The highly vulnerable ecological zones (total vulnerability weight score > 30) comprise the Mong Cai - Do Son coastal marine zone (Z.1) and the Mui Roon - Hai Van coastal marine zone (Z.4). The moderately vulnerable ecological zones (total vulnerability weighted score ranges from 10 to 30) include the Do Son - Lach Truong coastal marine zone (Z.2) and the Lach Truong - Mui Roon coastal marine zone (Z. 3). The ecological zones exhibiting low vulnerability (total vulnerability weight score < 10) consist of the northern marine zone of the Gulf (Z.5), the middle marine zone of the Gulf (Z.6) and the southern marine zone of the Gulf (Z.7). In Table 3, from the top to the sea bottom is depicted the order of decreasing

vulnerability of the ecosystems, and from left to right, the decreasing vulnerability of the ecological zones resulting from climate change - natural disasters.

***Vulnerability of marine ecosystems and ecological zones in the Gulf of Tonkin due to climate change and natural disasters***

*Influencing factors*

Regarding climate change and natural disasters, 10 main factors damage the marine ecosystems of the Gulf of Tonkin.

*Increased temperature* of surface seawater occurs gradually as a direct result of rising atmospheric temperatures. From 1958–2018, in Vietnam, the average annual temperature increased by about 0.15°C per decade. According to the medium scenario (RCP4.5), the average annual temperature in Vietnam will increase by 1.2–1.7°C by mid-century and by the end of the century by 1.6–2.4°C. [17]. Along with increasing atmospheric temperatures, rising seawater temperatures can change the sea’s biogeochemical cycle and

nutrient balance, food chains, biological community structure, and impact the species ecology and physiology. Some species can decrease in size, or even die, when temperatures spike. This factor affects all marine ecosystems, is stronger in the coastal ecosystems, and is most obvious in coral reefs and upwelling areas. During the El Niño of 1998, in the world's coral reefs, an average of 17.7% of corals died from bleaching due to rising water temperatures, of which 46% died in the Indian Ocean region, 33% in the Arabian region, and 18% in the East Vietnam Sea and Southeast Asia [42].

*Typhoons and waves* cause significant turbidization and re-sedimentation by stirring the sea bottom and damaging fragile ecosystems. These impacts are felt across all regions but are most intense in the coastal areas, especially within sandy beach and coral reef environments. Furthermore, the distribution of typhoons along the Vietnamese coast has undergone major changes in recent years [43]. However, strong typhoons tend to increase slightly [17]. On the west coast of the Gulf of Tonkin, the highest typhoon surge occurred at 3.5–4.4 m in 1958–2018, according to the different zones, and by the end of the 21<sup>st</sup> century, the highest forecast is 4.2–5 m.

*Rising sea levels* along the Vietnamese coast, which averaged an increase of 3.6 mm per year between 1958 and 2018, are projected to rise by an average of 52.5 cm in the Gulf of Tonkin by the end of the 21<sup>st</sup> century [17]. The rising sea level is a major threat of climate change, causing many negative impacts on the marine environment, such as flooding, coastal erosion and saltwater intrusion. The main impacts include deeper submerging and reduced ecosystem distribution, sometimes changing the biological community structure, especially for beaches, tidal flats, estuarine areas, and mangrove ecosystems. The sandy beach ecosystem is particularly sensitive to erosion due to rising sea levels.

*Turbidization* is driven by increased rainfall and catchment erosion, unusually high waves and strong typhoons, and the loss of mangrove forests that typically function to trap and deposit sediments. Annual rainfall tends to increase slightly in Vietnam, with an increase of

2.1% in 1958–2018, with a forecast increase of 10–15% by mid-century and 10–20% by the end of the 21<sup>st</sup> century [17]. Increased turbidization affects photosynthesis and the primary productivity of aquatic organisms. Sediment deposition can cause the death of corals [30], many plant species, especially seagrasses, and other benthic species. This factor strongly impacts the seagrass bed, coral reef, and lagoon ecosystems.

*Local freshening* occurs due to increased rainfall, unusually heavy rains, and when coastal water bodies become more closed due to inlet sedimentation. Freshening changes the species' ability to adapt, community structure, and even causes many species to die en masse. This impact is strongest on ecosystems such as lagoons [12], coral reefs [30] and seagrass beds [7].

*Salinization* changes the structure of biological communities and the adaptive ability of many species, affecting the structure and process of thermal-salt dynamics. In hot, dry years with little rain (the El Niño), due to a significant decrease in fresh water, sea surface water becomes salinized and the source of phosphorus from the sea bottom to the surface layer decreases, decreasing marine fish production [44]. Salinization affects offshore ecosystems, typically upwelling areas and near-closed coastal aquatic ecosystems, especially lagoons.

*Coastal erosion* is occurring intensely along many sections of the Gulf of Tonkin due to the combined impacts of human activities and climate change-driven natural disasters. These processes are primarily triggered by a shortage of sediment from upstream reservoirs and dikes, alongside the escalating pressures of rising sea levels, storms, and powerful waves. These factors cause the shrinkage or loss of habitats, even the partial loss of ecosystems such as sand beaches, estuarine areas, mangrove forests, and tidal flats.

*Circulation disturbances* are caused by alterations in the thermo-haline structure of offshore areas or changes in coastal landforms and the configuration of water bodies. In ENSO years, there have been large climate disturbances and the hydrological structure at sea can change abnormally. In the El Niño year of 1997–1998, the

warm Kuroshio current, passing through the southern sea of Japan, moved northward a considerable distance over three latitudes [46]. This factor potentially impacts on the upwelling ecosystems, sea bottoms, and coastal lagoons, so the upwelling ecosystem’s location is unstable, and the fishing grounds are shifting [16].

*Sedimentation* arises from increased sediment discharges from due to increased rainfall, coastal erosion releasing sediment, and typhoon waves stirring up the sea bottom and redepositing sediments. Sedimentation effects can shallow coastal waters, causing the death of benthic organisms and aquatic plants, especially in the lagoon ecosystems and seagrass beds. Sedimentation can also close coastal waters, causing freshening during the rainy season.

*Vulnerability of marine ecosystems due to climate change - natural disasters*

Table 2 presents the relationship matrix between nine climate change and natural disaster factors and their impacts on twelve distinct ecosystems. According to the level of impact, the climate change and natural disaster factors are divided into 3 groups: strong, medium, and weak. The group of strong impact factors (weighted score for each factor > 20)

includes increased water temperature, strong typhoons - high waves, and rising sea levels. The group of moderate impact factors (total weighted score for each factor ranges from 15–20) includes turbidization, local freshening, salinization, and erosion. The group of weak impact factors (total weighted score for each factor < 15) includes circulation disturbances and sedimentation. In Table 2, the level of impact of the factors related to climate change - natural disasters decreases from left to right.

According to the level of vulnerability induced by climate change and natural disasters, ecosystems are categorized into three vulnerability groups: high, medium, and low. The highly vulnerable ecosystems (total vulnerability score of each ecosystem > 15) comprise lagoons, seagrass beds, coral reefs, and beaches. The group of ecosystems with moderate vulnerability (the total vulnerability score of each ecosystem ranges from 11–15) consists of tidal flats, mangrove forests, estuarine areas, and permanent wetlands. The ecosystems demonstrating low vulnerability (total vulnerability weight score of each ecosystem < 11) include marine lakes, upwelling areas, sea bottoms, and rocky coasts. In Table 2, the ecosystem’s vulnerability is shown to decrease from the top to the sea bottom.

Table 4. Vulnerability weighted matrix of marine ecosystems in the Gulf of Tonkin due to climate change and natural disaster factors

No.	Ecosystems	Impact factors									Total
		i	ii	iii	iv	v	vi	vii	viii	ix	
1	Lagoon	1	2	3	2	3	2	2	1	3	19
2	Seagrass bed	2	2	2	3	3	1	1	1	3	18
3	Coral reef	3	3	0	3	3	1	1	1	1	16
4	Beach	2	3	3	2	1	1	3	1	0	16
5	Tidal flat	2	2	3	2	1	1	2	1	1	15
6	Mangrove forest	1	3	3	1	1	2	3	1	0	15
7	Estuarine area	1	2	3	1	1	1	3	1	1	14
9	Permanent wetlands	2	2	2	1	1	1	0	1	1	11
8	Marine lake	2	1	0	2	2	1	0	0	2	10
10	Upwelling area	3	1	0	0	0	3	0	3	0	9
11	Sea bottom	2	1	0	1	0	1	0	2	0	8
12	Rocky coast	2	0	2	1	1	1	0	0	1	8
Total		23	22	21	19	17	16	15	13	13	159

Notes: i- water temperature increase; ii- typhoons and waves; iii- rising sea levels; iv- turbidization; v- local freshening; vi- salinization; vii- erosion; viii- circulation disturbances; ix. sedimentation.

Table 5. Vulnerability weighted matrix of the marine ecosystems and ecological zones in the Gulf of Tonkin due to climate change - natural disasters

No.	Ecosystems	Ecological zones							Total
		Z.1	Z.4	Z.2	Z.3	Z.5	Z.6	Z.7	
1	Lagoon	0	19	0	0	0	0	0	19
2	Seagrass bed	5	6	3	4	0	0	0	18
3	Coral reef	5	4	0	4	3	0	0	16
4	Beach	4	5	2	4	1	0	0	16
5	Tidal flat	5	2	5	3	0	0	0	15
7	Mangrove forest	6	1	6	2	0	0	0	15
6	Estuarine area	2	2	7	3	0	0	0	14
8	Permanent wetlands	2	2	3	3	1	0	0	11
9	Marine lake	10	0	0	0	0	0	0	10
10	Upwelling area	0	0	0	0	5	4	0	9
11	Sea bottom	2	1	1	1	1	1	1	8
12	Rocky coast	4	1	0	2	1	0	0	8
Total		45	43	27	26	12	5	1	159

The Gulf of Tonkin (Vietnam part) includes seven different marine ecological zones. Each zone includes different typical marine ecosystems, and their level of vulnerability due to climate change and natural disasters has been determined (Table 4). From there, the level of vulnerability of the ecological zones and their matrix relationship with the level of vulnerability of each ecosystem in each zone have been determined (Table 5).

The Ecological zones exhibiting intense vulnerability (total vulnerability weight score > 30) include the coastal marine zone of Mong Cai - Do Son (Z.1) and the coastal marine zone of Mui Roon - Hai Van (Z.4). They characterized by moderate vulnerability (total vulnerability weight score ranges from 10–30) comprise the coastal marine zones of Do Son - Lach Truong (Z.2), the coastal marine zones of Lach Truong - Mui Roon (Z.3), and the northern marine zone of the Gulf (Z.5). The Ecological zones demonstrating low vulnerability (total vulnerability weight score < 10) consist of the middle marine zone of the Gulf (Z.6) and the southern marine zone of the Gulf (Z.7). In Table 3, from the top to the sea bottom is listed the order of decreasing vulnerability of the ecosystems, and from left to right is presented the order of decreasing vulnerability of ecological zones resulting from climate change - natural disasters.

***Overall assessment of the vulnerability of marine ecosystems in the Gulf of Tonkin due to human activities and climate change - natural disasters***

*Vulnerability levels of marine ecosystems*

In an overall assessment, the levels of vulnerability of marine ecosystems due to human activities and climate change - natural disasters are determined as follows: high vulnerability with a total weighted score > 30, moderate vulnerability with a total weighted score in the range of 20–30, and low vulnerability with a weighted score < 20. The order and the levels of vulnerability of the ecosystems are presented in Table 6.

In descending order, the group of marine ecosystems with a high level of vulnerability includes the following ecosystems: lagoons, estuarine areas, tidal flats, seagrass beds and coral reefs. In descending order, the group of marine ecosystems with a medium level of vulnerability includes the following ecosystems: beaches, mangrove forests, and permanent wetlands. In descending order, the group of marine ecosystems with a low level of vulnerability includes the following ecosystems: the sea bottom, marine lakes, rocky coasts, and upwelling areas.

Table 6. Total vulnerability weight scores and vulnerability levels of the marine ecosystems due to human activities and climate change - natural disasters in the Gulf of Tonkin

Order of vulnerability	Ecosystems	Human activities	Climate change - natural disasters	Total	Vulnerability levels
1	Lagoon	19	19	38	High > 30
2	Estuarine area	21	14	35	
3	Tidal flat	18	15	33	
4	Seagrass bed	15	18	33	
5	Coral reef	16	16	32	
6	Beach	13	16	29	Medium 20–30
7	Mangrove forest	14	15	29	
8	Permanent wetlands	17	11	28	
9	Sea bottom	10	8	18	Low < 20
10	Marine lake	7	10	17	
11	Rocky coast	9	8	17	
12	Upwelling area	5	9	14	
Total		164	159	323	-

*Vulnerability levels of marine ecological zones*

In an overall assessment, the levels of vulnerability of marine ecological zones due to human activities and climate change - natural disasters are established as follows: high

vulnerability with a total weighted score > 60; moderate vulnerability with total weighted scores between 40-60; and low vulnerability with weighted scores < 40. The order and the levels of vulnerability of the zones according to weighted scores are detailed in Table 7.

Table 7. Total vulnerability weight score and vulnerability levels of marine ecological zones due to human activities and climate change - natural disasters in the Gulf of Tonkin

Order of vulnerability	Ecological zones	Vulnerability Weight score due to human activities	Vulnerability Weight score due to climate change - natural disasters	Total vulnerability weighted score	Vulnerability levels
1	Z.1	49	45	94	High > 60
2	Z.4	44	43	87	
3	Z.2	30	27	57	Medium 40–60
3	Z.3	26	26	52	
5	Z.5	9	12	21	Low < 40
6	Z.6	4	5	9	
7	Z.7	2	1	3	
Total		164	159	323	-

The highly vulnerable ecological zones comprise the coastal marine zones of Mong Cai - Do Son (Z.1) and the coastal marine zones of Mui Ron - Hai Van (Z.4). The moderately vulnerable ecological zones include the coastal marine zone of Do Son - Lach Truong (Z.2) and the coastal marine zone of Lach Truong - Mui Ron (Z.3). The low vulnerable ecological zones consist of the northern marine zone of the Gulf

(Z.5), the middle marine zone of the Gulf (Z.6) and the southern marine zone of the Gulf (Z.7).

Marine ecological regions exhibit different levels of vulnerability due to human activities and climate change - natural disasters. The coastal marine region incorporates ecological zones Z.1, Z.2, Z.3, and Z.4, which demonstrate moderate to high vulnerability resulting from anthropogenic activities and climate change -

natural disasters. The open sea region encompasses ecological zones Z.5, Z.6, and Z.7, which are characterized by low vulnerability due to human activities and climate change - natural disasters.

## Conclusion

The Vietnamese Gulf of Tonkin hosts 12 typical ecosystems distributed across four coastal and three open-sea ecological zones. These include eight sea bottom-water body ecosystems (estuaries, lagoons, tidal flats, marine lakes, beaches, rocky coasts, permanent wetlands, and sea bottoms), three biological reef ecosystems (mangroves, seagrass beds, and coral reefs), and one water column-based ecosystem (upwelling area).

The marine ecosystem vulnerability is driven by nine human-related factors and eight climate change-related natural disaster factors. While both interact, the vulnerability stemming from human activities generally outweighs that caused by the natural disasters and climate change, though the latter is often exacerbated by human influence.

The vulnerability levels vary across the ecosystems: lagoons, estuaries, tidal flats, seagrass beds, and coral reefs face the high vulnerability, with lagoons and coral reefs specifically sensitive to both impact groups. The moderately vulnerable ecosystems include beaches (threatened primarily by natural disasters), mangroves, and permanent wetlands (affected mainly by human factors). The low vulnerability is observed in sea bottoms, marine lakes, rocky coasts, and upwelling areas.

Geographically, the coastal ecological zones exhibit higher vulnerability than open-sea regions. The coastal vulnerability peaks in the North (Z.1) and South (Z.4), with the moderate levels in the central zones (Z.2 and Z.3). Conversely, open-sea zones generally show the low vulnerability, which further decreases from the North (Z.5) to the South (Z.7).

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