












## REVIEW

# When Growth Meets Heritage: Rethinking Sustainability in a Vietnam's Coastal Frontier

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## ABSTRACT

This paper re-examines and synthesizes environmental and biodiversity data collected between 1995 and 2004 to reconstruct a reference baseline for the Hai Phong–Quang Ninh coastal system prior to Vietnam's most transformative phase of socio-economic development. This period—captured through extensive Vietnam–Italy scientific cooperation—documents one of the last scientifically recorded states of near-pristine environmental conditions in Ha Long Bay and its adjoining coastal waters, offering an indispensable benchmark for evaluating the magnitude and direction of change over the past twenty-five years. Over the past two decades, Vietnam's coastline has undergone profound transformation driven by industrial expansion, port construction, aquaculture, and mass tourism. Yet it remains unclear whether this growth has been sustainably absorbed by ecosystems of global significance, including the UNESCO World Heritage seascape of Ha Long–Cat Ba. By reinterpreting early-2000s baseline datasets, this paper provides a reference against which current and future ecological trajectories can be assessed and proposes indicator frameworks to support integrated

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coastal zone management and World Heritage conservation. Ultimately, the analysis highlights the enduring tension between rapid development and heritage protection, and it questions whether sustainable development in such complex coastal systems remains an achievable outcome or an aspirational ideal.

**Keywords:** Coastal Sustainability; Ha Long Bay; Socio-Ecological Transformation; Integrated Coastal Zone Management (ICZM); World Heritage Conservation

## 1. Introduction

This paper revisits and consolidates environmental and biodiversity datasets collected in the late 1990s and early 2000s to reconstruct a reference baseline for the Hai Phong–Quang Ninh coastal system—at a time when Ha Long Bay and adjacent waters still retained many features of near-pristine ecological conditions. This baseline, established before Vietnam’s major wave of industrialisation, port expansion, aquaculture intensification, and mass tourism, provides the essential temporal anchor for understanding how twenty-five years of accelerated socio-economic transformation have reshaped one of the country’s most valuable coastal and World Heritage regions. By foregrounding this reconstruction of the pre-development state, the study makes explicit from the outset that its primary aim is to clarify “where the system stood” before the most significant phase of change began.

Over the past two decades, Vietnam’s coastline has experienced rapid transformation following the Doi Moi reforms and subsequent integration into global markets. Industrial expansion, maritime trade, aquaculture, and tourism have redefined both livelihoods and landscapes, particularly in the Hai Phong–Quang Ninh coastal tract. Yet despite these gains, it remains uncertain whether such growth has been sustainably absorbed by the coastal environment or by the heritage values of sites such as Ha Long Bay and Cat Ba Island. Establishing a scientifically grounded baseline for the turn-of-the-century conditions is therefore not only for evaluating past and present trends but also for guiding future management, conservation, and policy decisions.

The coastal tract spanning Hai Phong municipality and Quang Ninh Province epitomizes the global dilemma of reconciling conservation with development. Within this zone, Ha Long Bay and Cat Ba Island—both internationally recognized for their Outstanding Universal Value—

have undergone profound transformation over the past two decades. Once sustained by modest fishing communities and low-impact tourism, the area has been reshaped by rapid growth in hospitality, mass tourism, port expansion, aquaculture, and large-scale industry. These investments generated substantial economic benefits and positioned the region as a driver of Vietnam’s growth, but also magnified environmental pressures, placing fragile ecosystems, cultural landscapes, and local livelihoods at risk. The situation underscores the urgent need for integrated coastal zone management, adherence to international commitments such as UNESCO conventions, and the use of tools like carrying-capacity assessments, marine spatial planning, and participatory governance to determine whether a balance between growth and heritage conservation can be sustained.

The reconstruction of this early-2000s reference state is not merely a historical exercise; it provides the only comprehensive snapshot of ecological conditions before developmental pressures intensified, allowing present-day assessments to distinguish natural variability from human-driven change with far greater precision. For any integrated management exercise aimed at achieving environmental sustainability together with social and economic viability, it is essential to establish measurable environmental and ecosystem metrics against which change can be evaluated. Without a clear reference point in time and space, assessments of degradation or recovery remain qualitative and inconclusive. Gauging system changes through such reference metrics, and assigning causal effects to specific human activities or natural processes, provides the analytical foundation for optimizing both natural and human systems. This approach turns sustainability from an abstract aspiration into a quantifiable process—where management actions can be adjusted toward outcomes that maximize ecological integrity and socio-economic benefit in a genuine win–win perspective.

Once potential impacts are anticipated, the challenge

lies in identifying patterns of decline and disentangling causal linkages between human actions and environmental consequences. This requires moving beyond acknowledging risks toward demonstrating how specific drivers—industrial development, land reclamation, mass tourism—translate into measurable changes in ecosystem health, biodiversity, and cultural landscapes. Establishing such linkages enables policymakers to design effective interventions, assign responsibilities, and target root causes rather than symptoms.

Developing a coastal baseline therefore goes beyond compiling ecological and socio-economic data: it requires systematic comparison with reference conditions representing historical states or agreed ecological thresholds. By selecting and monitoring indicators, researchers can identify not only the direction of change but also its significance for resilience, heritage values, and community well-being. This comparative framework transforms monitoring into a decision-support tool, guiding conservation strategies, UNESCO periodic reporting, and integrated coastal management where developmental pressures are intense.

The choice of temporal benchmark is critical, since it shapes how trends are interpreted. Establishing such a reference involves weighing data availability, the onset of major development pressures, and the feasibility of reconstructing earlier conditions. Once the reference is defined, critical indicators—water quality, habitat loss, species decline, socio-economic stressors—can be selected to capture both the magnitude of impacts and their drivers. In this way, the baseline becomes a diagnostic framework, integrating temporal reference, ecological signals, and socio-economic processes into a coherent system for tracking and managing change.

## 2. Objectives of the Review and Research Questions

This paper aims to crystallize the reference conditions that existed along the Hai Phong–Quang Ninh coastal tract at the turn of the century, to support further analyses of impacts and trends to date. This review aims to consolidate and interpret knowledge about the state of Hai Phong’s and Quang Ninh’s coastal and island districts in

support of long-term marine spatial planning. This baseline synthesis will help clarifying how socio-economic dynamics impacted environmental protection, biodiversity conservation, and sustainable livelihood goals.

The review also aims to inform policy and management through the application of Integrated Coastal Zone Management (ICZM) and Marine Spatial Planning (MSP)<sup>[1–3]</sup>. It provides an informative platform to assesses past condition of ecosystems and socio-economic systems, traces the drivers of change, and analyzes their impacts on environmental quality and social vulnerability. It helps evaluating the effectiveness of governance mechanisms and identifying critical knowledge gaps, while outlining the management options, technological innovations, and cooperative mechanisms needed to ensure that Hai Phong and Quang Ninh continue to develop as a sustainable maritime hub without undermining their ecological foundations.

## 3. Rationale for a Baseline Study in a UNESCO World Heritage Context

Establishing a comprehensive environmental and socio-ecological baseline is essential for safeguarding the Outstanding Universal Value (OUV) of World Heritage properties. As outlined in UNESCO’s Operational Guidelines, heritage protection must rest on sound, evidence-based understanding of environmental dynamics and pressures. Without such a foundation, management risks being reactive and fragmented rather than adaptive and forward-looking.

In the Ha Long Bay–Cat Ba Archipelago complex, whose OUV stems from exceptional karst landscapes, biodiversity, and long-standing human–environment interactions, a baseline study provides a systematic means to document these values and establish measurable reference points for assessing change. This is particularly urgent in the Hai Phong–Quang Ninh coastal system, where industrialization, port expansion, aquaculture, tourism, and climate change are generating cumulative pressures that threaten ecological integrity.

A robust baseline links science and governance by integrating environmental, socio-economic, and cultural

data into a common framework for decision-making. It promotes dialogue among scientists, managers, communities, and UNESCO advisory bodies (ICOMOS, IUCN, ICROM), ensuring accountability, compliance with reporting obligations, and evidence-based adaptive management.

Defining valid reference conditions—through historical records, paleo-ecological data, remote sensing, and oral histories—allows managers to track ecological health, carrying capacity, and cultural continuity over time. These reference states prevent ahistorical assessments and support early detection of decline or recovery.

Finally, baselines underpin risk assessment and resilience planning by providing data to model hazards, exposure, and adaptive capacity. They strengthen the credibility of national reports, contribute to global monitoring, and enable comparative learning across World Heritage sites facing similar pressures. By situating Hai Phong–Quang Ninh within this broader framework, the baseline enhances knowledge exchange, technical cooperation, and long-term conservation of its Outstanding Universal Value.

#### Turning Information into Insight

Over the past three decades, research on Vietnam’s coastal and marine environments has intensified, supported by expanding datasets and monitoring initiatives. Yet long-term trajectories remain insufficiently delineated in relation to a clear baseline. The absence of a reference point predating accelerated development constrains the ability to assess change rigorously and to distinguish natural variability (e.g., climatic) from anthropogenic impacts<sup>[4,5]</sup>.

While earlier studies had begun documenting pressures from industrialization, aquaculture, tourism, and port expansion<sup>[4]</sup>, underlying causal dynamics have not been later analyzed. This has limited the translation of findings into evidence-based policy, perpetuating a gap between knowledge generation and decision-making—an issue shared by other rapidly developing coastal regions worldwide.

Against this background, the present paper addresses the need for a reference baseline grounded on a coherent set of indicators to evaluate environmental change in the Ha Long Bay–Cat Ba–Quang Ninh–Hai Phong coastal system. Establishing such a baseline is essential for clarifying trajectories, guiding adaptive policy, and ensuring that conservation and development objectives are pursued in a

scientifically informed and sustainable manner.

## 4. The Need for a Baseline

As developmental pressures intensified under national growth demands, ecological stress became visible in Ha Long Bay and its hinterland by the early 2000s, coinciding with the global rise of biodiversity conservation after the Rio-92 Conference. Internationally, biodiversity protection gained traction through initiatives of the GEF, UNDP, UNEP, IUCN, and WWF<sup>[6–9]</sup>. Vietnam began integrating ecosystem health and biodiversity into its environmental legislation and planning frameworks.

Within this emerging framework of national and international environmental governance, the establishment of a scientific baseline becomes a prerequisite for assessing the state of ecosystems and biodiversity, defining reference conditions for monitoring change, and ensuring that conservation and management measures are grounded in objective, verifiable evidence.

#### Assumptions for a Reference Period

Three conditions guide the setting of a baseline reference:

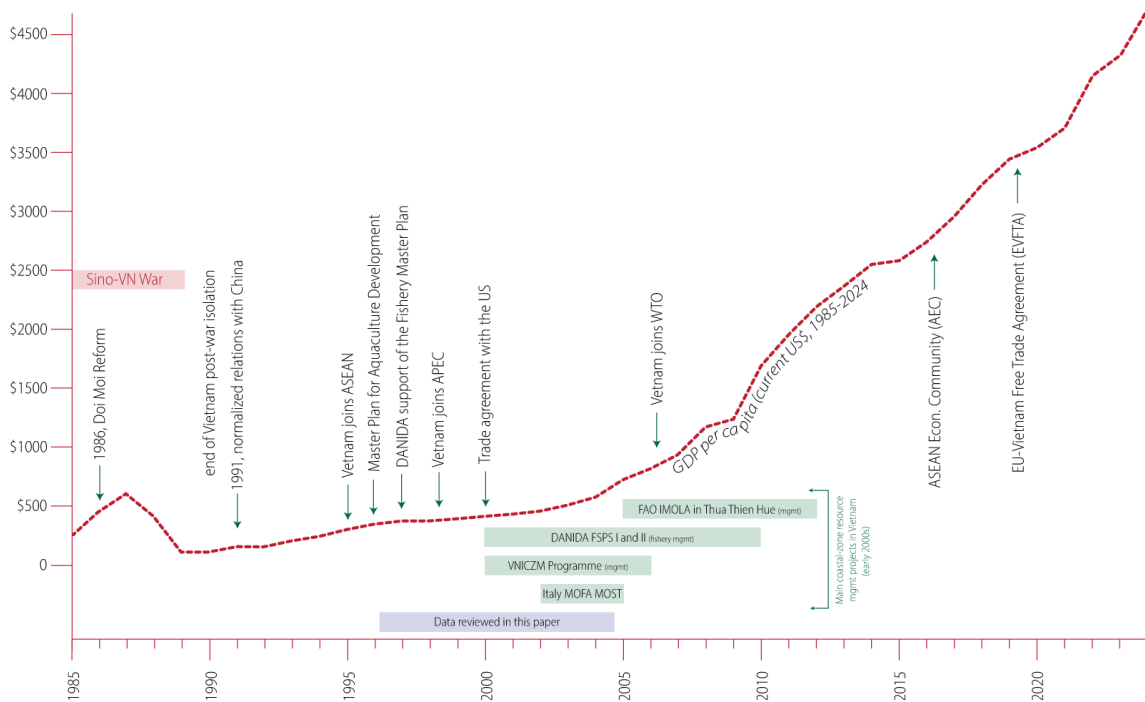
- Identify the onset of major development pressures (industrialization, port expansion, mass tourism).
- Ensure access to reliable historical data.
- Reconstruct earlier conditions using archival sources, remote sensing, palaeoecology, or oral histories.

The reference point must align with both ecological realities and socio-economic turning points. In Ha Long Bay–Cat Ba, this means examining phases before large-scale tourism and industrial expansion, while considering the availability of datasets. Developmental pressure rarely begins in a single year but arises from converging events, policies, and milestones<sup>[10,11]</sup>.

Vietnam’s trajectory illustrates this convergence. The Doi Moi reforms of 1986 initiated market liberalization, agricultural decentralization, and foreign investment<sup>[12]</sup> (**Figure 1**). By 1989, Vietnam ended its post-war isolation, normalizing relations with China in 1991 and later the United States, joining ASEAN (1995), APEC (1998), and signing a bilateral trade agreement with the U.S. in 2000. These reforms stimulated industrialization and tourism while encouraging aquaculture expansion, notably

through the 1996 Master Plan for Aquaculture Development and the DANIDA-supported 1997 Fisheries Master Plan. Aquaculture grew rapidly—shrimp and fish farming

expanded from 415,000 tons in 1997 to 590,000 tons in 2000—at significant ecological cost, including mangrove loss and habitat degradation.



**Figure 1.** Timeline of key socio-economic milestones, policies, and national interventions in Vietnam from the end of the war period to the present, shown against the long-term socio-economic development trajectory represented by GDP per capita. Data source: World Bank, licenced under CC BY-4.0.

Fisheries policy also shifted with subsidies introduced in 1997, contributing to overexploitation<sup>[13]</sup>. International development partners supported corrective initiatives: the Vietnam–Netherlands Integrated Coastal Zone Management Programme (2000–2006), DANIDA Fisheries Sector Programme Support (2000–2010), and FAO’s IMOLA project in Thua Thien Hue (2005). The IUCN Water & Nature Initiative (2003–2004) piloted environmental flow approaches in the Perfume River Basin.

Despite rising pressures, Ha Long Bay remained relatively pristine at the century’s turn, with tourism still incipient and infrastructure limited. By the early 2000s, however, UNESCO extended Ha Long’s heritage status to include geological values (2000), Cat Ba was designated a Biosphere Reserve (2004), and Vietnam began institutionalizing environmental management. MONRE was established in 2002, consolidating oversight of natural resources and environmental protection, while successive environmental laws (1993, 2005, 2014, 2020) created a legal framework for EIAs and pollution control. Yet en-

forcement lagged behind economic growth, generating persistent tensions.

These overlapping trajectories show that environmental stress in Vietnam’s coastal zone did not emerge suddenly but as the cumulative outcome of intertwined political, economic, and ecological processes. The years 1997–2002 capture both the intensification of pressures and the government’s first corrective measures, making this period a meaningful reference for baseline assessments.

## 5. Conceptual and Methodological Foundations

### 5.1. Baseline Studies in UNESCO Heritage Management

In heritage management, baseline studies are essential for defining the attributes that convey Outstanding Universal Value (OUV) and for assessing authenticity and

integrity over time. In the Ha Long Bay–Cat Ba Archipelago, this requires going beyond biodiversity to include karst landscapes, cultural practices, and the social-ecological systems linking communities to their environment. Such baselines allow managers to track how heritage values are preserved or transformed under socio-economic pressures.

Because natural and cultural values are interdependent, baselines must be multidisciplinary, combining ecological data with historical records, oral traditions, and archaeological evidence. They are not static inventories but dynamic tools that inform vulnerability assessments, guide monitoring, and ensure compliance with national and international commitments. In the context of ICZM and MSP, they provide the evidence base for reconciling development with conservation, ensuring that environmental protection and heritage safeguarding advance together.

## 5.2. Defining Environmental Health in Coastal and Marine Systems

Environmental health in coastal and marine systems refers to the condition in which the physical, chemical, and biological characteristics of these environments are maintained within ranges that sustain ecosystem integrity, support biodiversity, and provide the ecological services essential to human well-being. It implies that water quality, habitats, and living resources remain resilient to natural variability and human pressures, and that socio-economic activities such as fishing, tourism, port operations, and aquaculture are carried out without undermining ecological functions or public health.

In the DPSIR (Drivers-Pressures-State-Impacts-Responses) framework, environmental health in coastal and marine systems is the dynamic balance whereby human drivers and pressures alter ecosystem states and services, producing impacts that require societal responses to sustain resilience and well-being.

In practical terms, environmental health is assessed through indicators such as water and sediment quality, species diversity, the extent and vitality of critical habitats (e.g., mangroves, seagrass beds, coral reefs), and the capacity of ecosystems to absorb disturbances while continuing to provide services like coastal protection, nutrient

cycling, and fisheries productivity. In coastal zones with World Heritage values, environmental health also encompasses the safeguarding of cultural landscapes and traditional resource uses that are integral to heritage resilience.

## 5.3. Establishing a Pre-Development Coastal Reference (1995–2004) for Hai Phong and Quang Ninh: Methods and Indicators

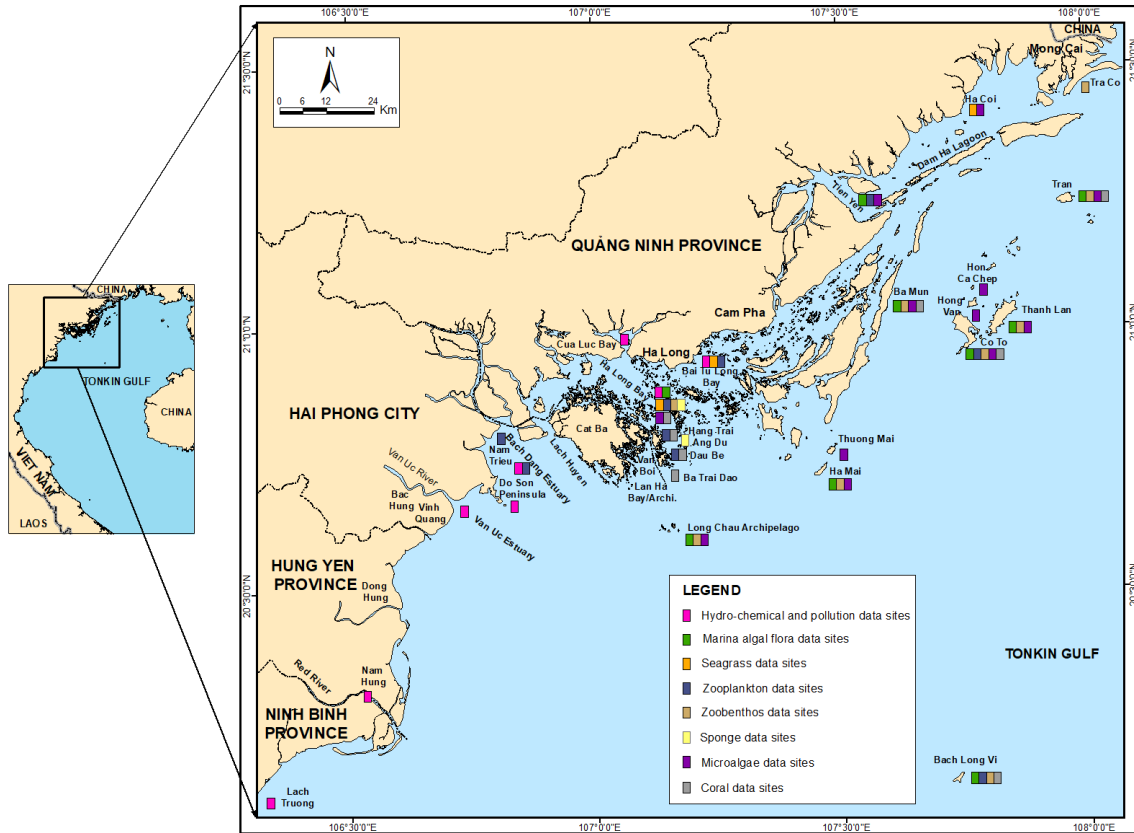
Establishing a meaningful environmental baseline requires the careful selection of indicators that can capture the complexity of estuarine and shallow shelf ecosystems. Indicators are measurable biological, chemical, and physical variables that act as proxies for ecosystem condition. They distill complex processes into tractable metrics, facilitating the detection of environmental change and providing decision-makers with an evidence base for management. The choice of indicators is not only a technical matter but also an epistemic one: it reflects which ecological processes are considered most relevant to track, which pressures are most acute, and what management responses are feasible in the given socio-economic context.

### 5.3.1. Criteria for Indicator Selection

A baseline study must ensure that selected indicators are:

- Ecologically relevant—linked to key processes such as nutrient cycling, hydrodynamics, or habitat resilience.
- Sensitive to change—responsive to stressors such as eutrophication, pollution, or habitat alteration.
- Measurable and comparable—allowing consistent monitoring across space and time, with reference to established methodologies.
- Policy-relevant—aligned with national environmental standards and international frameworks (e.g., UNEP Regional Seas, Marine Strategy Framework Directive descriptors, SDG 14 indicators).

These criteria are particularly important in semi-enclosed systems like Ha Long Bay, where anthropogenic pressures intersect with high ecological diversity (**Figure 2**).



**Figure 2.** Context map of the Tonkin Gulf coastal system across Quang Ninh Province and Hai Phong Municipality, extending from the Vietnam–China border to the Red River Delta.

The map shows all locations referenced in the text and indicates the type of environmental and ecological data analysed in the study through colour-coded symbols, including hydro-chemical and pollution data, marine algal flora, seagrass, zooplankton, zoobenthos, sponge, microalgae, and coral datasets.

### 5.3.2. Indicators for Estuarine Environments (Tonkin Gulf River Mouths)

Estuarine systems, where freshwater and seawater mix, require indicators that capture gradients in salinity, nutrient enrichment, and pollutant loading. Key categories include:

- Physico-chemical indicators: salinity, turbidity, dissolved oxygen, and nutrient concentrations (N, P) provide insight into stratification, eutrophication potential, and hypoxia.
- Biological indicators: phytoplankton biomass (chlorophyll-a), benthic macroinvertebrate community

indices (e.g., AMBI), and fish nursery abundance reflect ecosystem function and pollution sensitivity.

- Pollution indicators: heavy metal accumulation in sediments and filter-feeding organisms (mussels, oysters), as well as microbial contamination (coliform bacteria), indicate human pressures such as industrial discharge and untreated sewage.

### 5.3.3. Indicators for Shallow Shelf Environments (Ha Long Bay)

The shallow shelf of Ha Long Bay presents a different monitoring challenge. As a UNESCO World Heritage site, it is characterized by karstic seascapes, semi-enclosed circulation, and high ecological value. Appropriate indicators include:

- Hydrological indicators: residence time, circulation patterns, and stratification events, which govern flushing capacity and pollutant retention.
- Biological indicators: coral and sponge cover, sea-

grass extent, and foraminiferal assemblages as proxies for benthic health and sediment quality.

- Sediment indicators: granulometry, organic carbon content, and pollutant loads serve as long-term records of environmental change.
- Habitat integrity indicators: extent of mangroves, seagrass, and coral communities, which act as sentinels of water quality and coastal stability.

### 5.3.4. Integrating Indicator Domains

The guiding principle in building a baseline is integration across domains. Pollution, biodiversity, climate change, fisheries, and habitat health are not discrete but interdependent. For instance, nutrient enrichment (pollution domain) may drive algal blooms that reduce oxygen and impact benthic macrofauna (biodiversity domain), which in turn affects fisheries productivity. In Ha Long Bay, coral bleaching (climate impact indicator) can cascade into reduced fish biomass (fisheries indicator) and diminished reef habitat complexity (habitat indicator). Thus, a robust baseline should adopt a cross-domain perspective, selecting a core set of indicators that capture pressures, states, and responses simultaneously.

### 5.3.5. Towards a Baseline Framework

For the Tonkin Gulf and Ha Long Bay, an operational baseline framework could include:

- Core pollution indicators: nutrient concentrations, heavy metal levels, microplastic abundance.
- Core biodiversity indicators: species richness/diversity, coral and seagrass cover, invasive species occurrence.
- Core climate indicators: sea surface temperature, pH (acidification), sea level trends.
- Core fisheries indicators: catch per unit effort (CPUE), stock biomass, bycatch rates.
- Core habitat indicators: benthic community indices, mangrove/seagrass/coral extent.

By applying these indicators in a consistent and standardized manner, it becomes possible to reconstruct environmental trajectories, identify early warning signs of degradation, and measure progress towards sustainable

management goals. The subsequent chapter will build upon this foundation to outline how indicator data can be systematically organized into a coherent environmental baseline for the Tonkin Gulf and Ha Long Bay.

## 6. Hai Phong Estuary and Quang Ninh Coastal Zone Context

This section provides a concise synthesis of the physical setting, climate and resources of the Hai Phong estuary and the adjoining Quang Ninh coastal tract.

### 6.1. Physical Environment

The Hai Phong–Quang Ninh coastal region lies at the transition between the ancient Northeastern Highlands and the younger Hanoi–Red River rift zone, where intersecting fault systems linked to the Red River fault create a geologically complex landscape. Alternating uplifts—such as Kien An–Do Son, Thuy Nguyen–Quang Yen, and Cat Ba—and subsiding basins around the Bach Dang estuary define a tectonically active area with moderate seismic risk. Extensive Quaternary deposits continue to accumulate in low-lying areas, attesting to ongoing subsidence and sedimentation processes<sup>[14]</sup>.

Geomorphologically, about 85% of the region consists of flat alluvial plains, built by Red and Thai Binh River sediments, interspersed with limestone hills and karst uplands rising to about 200 meters. The coastline is dynamic, with alternating erosion and accretion zones, while offshore the Ha Long Bay–Cat Ba Archipelago forms one of the world’s most spectacular tropical karst seascapes, recognized as a UNESCO World Natural Heritage Site in 2023.

The climate is humid tropical monsoon with two distinct seasons: a hot, wet summer (May–September) influenced by the southwest monsoon and a cool, dry winter (November–March) under the northeast monsoon. Average annual temperatures are around 23–24 °C, with summer highs up to 38 °C and winter lows occasionally below 10 °C. Rainfall totals 1600–1800 mm per year, about 80–90% of which occurs during the wet season, while the dry months are marked by drizzle and fog. Relative humidity averages 84–85%, and annual sunshine reaches 1600–1900 h.

Ecologically, the Quang Ninh–Hai Phong system supports an exceptional mosaic of marine and coastal ecosystems shaped by its karst topography and wide tidal range (up to 4 m). Habitats include mangroves, seagrass beds, coral reefs, tidal flats, and semi-enclosed lagoons. The Ha Long–Cat Ba area hosts the highest coral density in the Gulf of Tonkin—up to 94% coverage around Bach Long Vi Island—while mangroves in Mong Cai, Quang Yen, Cat Hai, and Tien Lang provide critical coastal protection and nursery grounds. Over 130 lagoons (*Ang* and *Tung*) within Ha Long and Cat Ba serve as biodiversity refuges of high ecological and scenic value.

Together, these geological, climatic, and ecological systems form an integrated land–sea continuum that sustains rich biodiversity and vital ecosystem services.

## 6.2. Resources (Biological and Non-Biological)

The Hai Phong–Quang Ninh coastal zone supports rich biological and mineral resources that underpin both local livelihoods and industrial development<sup>[14]</sup>. Productive marine waters around Cat Ba and Bach Long Vi sustain diverse fisheries of fish, crustaceans, and mollusks, while mangrove areas such as Tien Lang and Do Son serve as nursery grounds and support widespread aquaculture

In sheltered bays and tidal flats, these living resources are ecologically vital but increasingly threatened by overexploitation and coastal development. On land, fertile alluvial soils have long supported agriculture and now accommodate expanding industrial zones, while limestone, sand, clay, and other construction minerals are actively quarried for Hai Phong’s building industry. Quang Ninh’s coal reserves remain a major national energy source, complemented by the Gulf of Tonkin’s offshore oil and gas prospects and growing potential for wind and solar power. Together, these biological and non-biological resources represent the economic foundation of the region, whose sustainable use is essential to balancing development with environmental protection.

## 7. Early 2000s Benchmark: Biodiversity and Ecosystem Decline

To establish a robust baseline for this paper, we draw upon a critical benchmark: the Vietnam–Italy scientific co-

operation project “*Biodiversity Conservation in the Coastal Zone of Vietnam*” (2002–2004), undertaken within the bilateral framework between the Ministry of Science and Technology of Vietnam and the Italian Ministry of Foreign Affairs. Implemented by the Hai Phong Institute of Oceanology, in collaboration with the University of Ancona, the project produced the first systematic biodiversity assessments for Ha Long Bay, Bai Tu Long, Cat Ba, and adjacent coastal zones.

By combining field surveys, inventories, and literature reviews, it identified key ecosystems, biodiversity “hotspots,” and areas most vulnerable to pressures such as overfishing, aquaculture expansion, industrialization, and climate variability. Beyond its scientific value, the report set an early agenda for conservation priorities and management interventions in Vietnam’s coastal provinces. In the context of this paper, it provides a reference point for reconstructing ecological conditions in the early 2000s, thereby enabling policymakers and planners to evaluate subsequent trends in biodiversity, inform spatial planning, and align conservation strategies with sustainable development goals. Moreover, it connects to Vietnam’s commitments under the Convention on Biological Diversity (CBD), the Integrated Coastal Zone Management (ICZM) agenda, and UNESCO’s World Heritage and Man and the Biosphere (MAB) frameworks, reinforcing its relevance as a foundational document for both national policy and international cooperation.

The project objectives were to strengthen biodiversity management in Vietnam’s coastal zone—with particular attention to typical ecosystems, rare, endangered, and endemic species—by gathering comprehensive information on species and ecosystem diversity, preparing biodiversity “hotspot” maps, and proposing strategies for sustainable use and protection.

### 7.1. Biodiversity Inventories and Reference Data

Between 2002 and 2003, more than 3700 species were recorded from Tra Co (Mon Cai) to the Hai Van pass (Thua Thien Hue), including mangroves (115 species), phytoplankton (494), seaweeds (259), zooplankton (207), zoobenthos (1790), corals (199), marine fishes (555), and sponges (161, some of them potentially new to science).

These data were complemented by a review of more than 270 earlier reports and research programs, providing historical depth to the assessment. The study also produced the first biodiversity checklists and preliminary zonation maps, identifying four sub-regions of biodiversity along the coast and highlighting sensitive areas such as Lan Ha Bay and Co To–Thanh Lan as “hotspots.”

The Vietnam-Italy project reports established a critical reference dataset for early 2000s biodiversity status in the Quang Ninh–Hai Phong coastal system, invaluable for monitoring subsequent change.

## 7.2. Ecosystem Health and Function Integrity Evaluation.

The report also makes clear that already in the early 2000s there was a growing perception of biodiversity loss and ecosystem decline in Vietnam’s coastal zone, even though the most intense development pressures were only beginning to emerge.

Natural disturbances such as typhoons and seasonal heat extremes combined with early signals of human impact—most prominently the rapid expansion of aquaculture encouraged by national promotion policies of the mid-1990s—to erode habitat quality and reduce populations of rare species such as lobster and abalone.

Evidence presented in the project’s findings illustrates how these pressures had already translated into measurable decline. In the Mekong delta, mangrove forests shrank from 154,000 ha in 1943 to just 15,174 ha in 1995 (a loss of nearly 2700 ha per year). In Quang Ninh and Hai Phong, thousands of hectares of mangroves in Yen My, Dong Rui, Cai Dam, Dinh Vu, and Tien Lang were cleared and converted into aquaculture ponds, fundamentally altering tidal wetland habitats. Tidal flats in the Red River estuary were reduced by 500–600 ha per year through reclamation. Coral reefs showed a particularly alarming decline: around Cat Ba Island, 58% of surveyed reefs were already ruined or degraded, while live coral cover at Bach Long Vi collapsed from 95% in 1993 to 20% by 1999. The ecological decline carried direct economic consequences: aquaculture ponds established on newly cleared mangrove land lost 50–90% of their productivity within 3–5 years, and zoobenthos biomass in degraded Cat Ba reefs fell to just 0.29% of that in nearby healthier Ha Long reefs. At

the national scale, ground-fish stocks declined by 46% between 1984 and the early 1990s, leading to collapsing catch yields.

These intertwined ecological and socio-economic signals were interpreted at the time as early warnings: ecosystems that had long supported rich biodiversity and livelihoods were already under stress and showing signs of collapse. In the context of this paper, that perception provides the starting point for reconstructing baseline conditions in the early 2000s, against which the acceleration of development and its ecological consequences can now be critically assessed. This makes the 2002–2004 Vietnam–Italy cooperation project an indispensable reference for baseline reconstruction in this study.

## 8. Baseline Environmental Conditions in the Quang Ninh–Hai Phong Coastal Waters (1995–2004)

### 8.1. Hydrochemical and Pollution Characteristics—Quang Ninh to Do Son Peninsula

In the late 1990s and early 2000s, the northern coastal waters of Vietnam displayed complex hydro-chemical dynamics shaped by tidal exchange, river inflows, and increasing human pressure<sup>[14]</sup>. Salinity remained high and stable during the dry season (18–32‰ in Quang Ninh; 5–30‰ in Hai Phong) but declined sharply during the rainy season under the influence of the Red and Thai Binh rivers, particularly near the Bach Dang estuary. pH values (7.9–8.4) remain slightly alkaline throughout the year, sustaining ecological stability. Three subzones were identified: Quang Ninh–Do Son (stable, high salinity/pH), Do Son–Lach Truong (declining, fluctuating), and further south (increasing again).

During this period, water quality deteriorated progressively under mounting pressures from industrial, urban, aquaculture, and agricultural discharges.

Nutrient levels reveal growing anthropogenic stress. Ammonium largely complies with national standards, yet nitrite and phosphate concentrations have risen markedly since the late 1990s, reflecting wastewater and agricultural runoff (**Table 1**). This trend signals a gradual shift toward

eutrophication, especially in semi-enclosed and estuarine waters.

Oil contamination emerged as a chronic issue between 1995 and 2001, with concentrations averaging 0.5 mg/L—well above the 0.3 mg/L standard—and highest in Cua Luc and Bach Dang. The pollution risk index increased from 0.8 to 2.7, linking hydrocarbon accumulation

to expanding port activity and maritime traffic (Table 2).

Suspended solids constitute another pervasive stressor, frequently exceeding Vietnamese standards. Concentrations range from 2–100 mg/L in Ha Long–Bai Tu Long and up to 1500 mg/L in the Do Son–Ba Lat sector during floods, with more than 70% of samples surpassing thresholds for coral reef and bathing-water protection (Table 3).

**Table 1.** Temporal trends in ammonium, nitrate, and phosphate concentrations at four sites in Ha Long Bay (Cua Luc, Vinh Ha Long) and Hai Phong (Do Son, Bach Dang) during 1996–2000.

Year	Cua Luc			Vinh Ha Long			Do Son			Bach Dang Estuary		
	Ammonium (µg/L)	Nitrite (µg/L)	Phosphate (µg/L)	Ammonium (µg/L)	Nitrite (µg/L)	Phosphate (µg/L)	Ammonium (µg/L)	Nitrite (µg/L)	Phosphate (µg/L)	Ammonium (µg/L)	Nitrite (µg/L)	Phosphate (µg/L)
1996	<100	3	4.4	<100	2.5	6.6	<100	4.5	4.1	<100	6.8	10.6
1997	<100	6.5	17.2	<100	5.6	20.5	<100	10.9	13.2	<100	9.5	28.5
1998	<100	6.3	25.2	<100	4.8	17.8	<100	18.9	29.8	<100	14.5	30.6
1999	<100	10.5	9.6	<100	6.8	19.2	<100	18.2	18.4	<100	15.2	23.4
2000	<100	10.7	25.2	<100	7	21.4	<100	18.4	35.4	<100	17.8	33.8
Ammonium values are expressed qualitatively (“mostly < 100 µg/L”) since the dataset was presented in percentage categories, not continuous averages.			Ammonium concentrations remained below the 100 µg/L bathing guideline in most samples.			Ammonium values are expressed qualitatively (“mostly < 100 µg/L”) since the dataset was presented in percentage categories, not continuous averages.			Ammonium exceeded 100 µg/L in a small fraction of samples, making this area one of the few with occasional breaches of bathing water standards.			

**Table 2.** Average risk quotient (RQ) from oil contamination, for the northern coastal zone of Vietnam, based on data from Cua Luc, Cua Bach Dang, Cua Ba Lat, and Sam Son estuaries.

Location	1995	1996	1997	1998	1999	2000	2001
Cua Luc	0.9	2.1	1.6	2	2.5	2.7	2.7
Cua Bach Dang	1.1	1.8	1.2	1	1.6	1.7	2.2
Overall area	0.8	2.1	1.4	1.8	2.1	2	2.2

Note: Average risk index (RQ) for the entire northern coastal zone, calculated from all the individual sites (Cua Luc, Cua Bach Dang, Cua Ba Lat, Sam Son).

**Table 3.** Total suspended solids (TSS) in coastal waters at four sites between Thanh Hoa (Sam Son) and Quang Ninh (Bai Tu Long), encompassing the Red River Delta and Ha Long Bay Archipelago, during dry (October–April) and rainy (May–September) seasons.

Coastal Area	Dry Season (mg/L)	Rainy Season (mg/L)	% Exceedance of Standards	Notes
Ha Long–Bai Tu Long	2–100	5–150	72% > 10 mg/L (coral reef); 60% > 25 mg/L (bathing)	Lowest values overall but high ecological risk
Lach Huyen – Do Son	15–250	20–400	Frequent exceedance of > 50 mg/L (aquaculture)	River-influenced, higher than Quang Ninh
Do Son – Ba Lat	20–300	50–1500	50–86.5% > 50 mg/L (rainy); up to 53.2% > 50 mg/L (dry)	Most turbid zone, extreme rainy-season peaks
Ba Lat – Sam Son	15–200	20–300	Frequent exceedance of > 50 mg/L (aquaculture)	Less severe than Do Son – Ba Lat but still high

Heavy-metal monitoring since the mid-1990s indicates estuarine accumulation, with copper, lead, and zinc (Table 4), mostly below national limits but cadmium and mercury posing persistent risks. Cadmium frequently exceeds the 5 µg/L standard, while mercury, though compliant with Vietnamese norms, often violates stricter ASEAN criteria (Table 5).

Despite a formal ban in 1994, organochlorine pesticides (OCPs) remain detectable due to continued illicit use and their persistence in sediments. DDT and its metabolites dominate, with Ba Lat emerging as the most contaminated site (up to 0.688 µg/L). Risk quotients for total DDT reach extreme levels (7–117), underscoring long-term ecological hazards (Table 6).

**Table 4.** Heavy metal concentrations at the estuaries of the Bach Dang (Hai Phong) and Ba Lat–Red River (Thai Binh/Nam Dinh provinces).

Metal	Range (µg/L)	Average (µg/L)	Standard (µg/L)	Risk Index (RQ)	Hotspots/Notes
Copper (Cu)	0.9–1.5	1.2	10 (VN aquaculture)	Up to 1.5	Elevated at Bach Dang, Ba Lat; moderate pollution risk
Lead (Pb)	0.5–60	5.8	50 (VN aquaculture)	~0.1	Generally low; slightly higher in Bach Dang and Ba Lat
Zinc (Zn)	1.6–9.9	3.9	10 (VN aquaculture)	0.9–4.9	Approaching limit; highest risk in Bach Dang and Ba Lat
Cadmium (Cd)	0.5–60	5.4	5 (VN aquaculture)	>1 (often exceeded)	Most problematic; frequent exceedance, especially in Bach Dang and Ba Lat
Arsenic (As)	1.20–10.70	2.82	10 (VN aquaculture)	0.20–0.42 (avg. 0.28)	Low levels; no clear pollution
Mercury (Hg)	0.01–3.10	0.44	5 (VN)/0.14 (ASEAN)	0.04–0.21 (VN); 1.6–7.4 (ASEAN)	Acceptable under VN standards; problematic under ASEAN criteria

**Table 5.** Heavy metal risk quotient (RQ) at Cua Luc (Ha Long), Bach Dang (Hai Phong), and Ba Lat–Red River (Thai Binh–Nam Dinh), calculated against national threshold values.

Metal	Standard (µg/L)	Cua Luc (RQ)	Bach Dang (RQ)	Ba Lat (RQ)	Other Areas (RQ)	Notes
Copper (Cu)	10	~1.2	Up to 1.5	Up to 1.5	<1	Localized exceedance in Bach Dang and Ba Lat
Lead (Pb)	50	~0.1	~0.15	~0.15	~0.1	Generally low; slightly higher in Bach Dang and Ba Lat
Zinc (Zn)	10	~0.4	4.9	4.9	<1	Elevated at Bach Dang and Ba Lat
Cadmium (Cd)	5	>1	>1 (2–3)	>1 (2–3)	<1	Most problematic; frequent exceedance
Arsenic (As)	10	0.28	0.28	0.28	0.28	No significant pollution
Mercury (Hg)	5 (VN)/0.14 (ASEAN)	0.09 (VN); 3.1 (ASEAN)	0.09 (VN); 3.1 (ASEAN)	0.09 (VN); 3.1 (ASEAN)	0.09 (VN); 3.1 (ASEAN)	Acceptable under VN standards; polluted under ASEAN

**Table 6.** Organochlorine pollution risk quotient (RQ) at Cua Luc (Ha Long), Bach Dang (Hai Phong), Ba Lat–Red River (Thai Binh–Nam Dinh), and Sam Son (Thanh Hoa), calculated for dry (October–April) and rainy (May–September) seasons.

Site	Dry Season (µg/L)	Rainy Season (µg/L)	Pollution Risk (RQ)	Notes
Ba Lat	0.688	0.362	Total DDT RQ 7.1–117.5 (avg. 48.3)	Most contaminated site, hotspot for DDT and derivatives
Sam Son	↑ in dry season	↓ in rainy season	Elevated RQ values	Seasonal inversion vs. Ha Long–Bach Dang
Cua Luc	Moderate	Higher in rainy	Moderate risk	Similar seasonal pattern to Ha Long–Bach Dang
Do Son	Moderate	Higher in rainy	Moderate risk	Similar seasonal pattern to Cua Luc
Tra Co	0.085	0.007	Lowest risk	Cleanest site

At that time, the region, situated within Vietnam’s key northern economic development zone, was under growing pollution pressure. These conditions posed risks to ecosystems and local livelihoods, underlining the urgent need for environmental management and pollution control to sustain the ecological and economic potential of the northern coastal waters.

## 8.2. Marine Algal Flora of Northern Vietnam

Covering a 1000 km stretch of coastline from Mui Sa Vi (Quang Ninh) to Hai Van Pass (Thua Thien Hue), the Vietnam-Italy project’s synthesis provides the most comprehensive account of northern Vietnam’s marine algae. Surveys conducted since the 1990s under national and international standards documented 264 species belonging

to Cyanophyta, Rhodophyta, Phaeophyta, and Chlorophyta (Table 7).

Species composition and distribution are highly heterogeneous, reflecting the complex geomorphology and variable tidal regimes of the region. Species richness ranged from as few as 6 species in Tien Yen Bay to 102 in Ha Long Bay, with secondary peaks at Cat Ba (71) and Lang Co (Thua Thien Hue) (84). Sorensen similarity indices reveal low floristic overlap among most sites, highlighting distinct local assemblages and biodiversity hotspots concentrated around Quang Ninh (Ha Long–Cat Ba). Peripheral and more exposed areas such as Tien Yen and Nghi Son host impoverished floras, likely due to longer tidal exposure and higher thermal stress (Table 8).

**Table 7.** Number and proportion of algal species by phylum in Vinh Ha Long and Vinh Bai Tu Long (Hai Phong–Mong Cai sector, Gulf of Tonkin).

Group	Number of Species	Percentage (%)
Cyanophyta (blue-green algae)	16	6.1
Rhodophyta (red algae)	121	45.8
Phaeophyta (brown algae)	71	26.9
Chlorophyta (green algae)	56	21.2

**Table 8.** Sorensen similarity coefficient (S) of marine algae in northern Vietnam.

	Tien Yen Bay	Long Chau Archipelago	Tran Island	Ha Mai Island	Ba Mun Island	Thanh Lan–Co To	Bach Long Vy	Cat Ba Archipelago	Ha Long Bay
Tien Yen Bay	0	0	0.05	0.01	0	0	0	0	0
Long Chau Archipelago	0.07	0.01	0.02	0.13	0.1	0.15	0.09	0.04	0.11
Tran Island	0.03	0.06	0.17	0.03	0.05	0.05	0.08	0.02	0.08
Ha Mai Island	0	0.1	0.01	0.02	0.02	0.02	0.03	0.04	0.02
Ba Mun Island	0	0	0.06	0.09	0.05	0.04	0.15	0.01	0.04
Thanh Lan–Co To	0	0	0	0.05	0.12	0.04	0.08	0.14	0.11
Bach Long Vy	0	0	0	0	0.06	0.03	0.09	0.07	0.06
Cat Ba Archipelago	0	0	0	0	0	0.19	0.01	0.05	0.16
Ha Long Bay	0	0	0	0	0	0	0	0.14	0

Vertically, about 75% (199 species) occur in the intertidal zone, while 29% (77 species) inhabit subtidal zones, showing adaptation to different light, temperature, and desiccation regimes.

The floristic index ( $C = 2.32$ ), calculated from Cheney’s formula, identifies the algal flora as warm-temperate, typical of transitional coastal regions influenced by both tropical and subtropical conditions.

Overall, the study outlines a biogeographically diverse yet locally distinctive algal community, structured by geomorphology, tidal dynamics, and climatic gradients along the northern Vietnamese coast.

## 8.3. Seagrasses Assemblages and Conservation Issues in Quang Ninh–Hai Phong

Zoning approaches for seagrass protection increas-

ingly require integrated frameworks that combine ecological sensitivity, spatial planning, and socio-economic considerations to support sustainable coastal management [15]. Such frameworks provide decision-makers with robust tools to balance conservation priorities with human uses in dynamic lagoon and near-shore environments.

Addressing the conservation status, research gaps, and current knowledge of seagrass habitats within World Heritage properties is essential to ensure the effective protection of these highly productive ecosystems and the ecosystem services they provide at global scale [16].

Seagrass meadows in Quang Ninh–Hai Phong represent vital coastal ecosystems that underpin both marine biodiversity and local livelihoods. They stabilize sediments, buffer shorelines, and sustain rich biological assemblages—over 120 benthic species, 150 seaweeds, and 58

epiphytic algae—while interlinking functionally with mangroves and coral reefs to enhance ecosystem resilience.

Research on Vietnam’s seagrasses began in the mid-1990s through the pioneering studies of Nguyen Van Tien, which first identified species composition and stressed their conservation significance.

In Quang Ninh, six seagrass species were recorded between 1995 and 2002, belonging to four families and five genera, with the Hydrocharitaceae being the most diverse [17,18]. Dominant species such as *Zostera japonica*, *Halophila ovalis*, and *Ruppia maritima* typify four main habitat types: tidal flats and nearshore islands, estuarine–mangrove areas, aquaculture ponds, and semi-enclosed bays and lagoons (e.g., Dam Ha, Ha Coi, Ha Long, Bai Tu Long) (Table 9).

**Table 9.** Species composition of seagrasses in Northern Vietnam coastal seas and Quang Ninh Province.

Species Designation (with Vietnamese Name)	Family	Presence in Quang Ninh
<i>Halophila beccarii</i> Asch. (cỏ năn)	Hydrocharitaceae	+
<i>Halophila decipiens</i> Ostenf. (cỏ xoan đom)	Hydrocharitaceae	
<i>Halophila ovalis</i> (R.Br.) Hooker (cỏ xoan)	Hydrocharitaceae	+
<i>Halophila minor</i> (Zoll.) Den Hartog (cỏ xoan nhỏ)	Hydrocharitaceae	+
<i>Thalassia hemprichii</i> (Ehr.) Asch. (cỏ vích)	Hydrocharitaceae	
<i>Halodule pinifolia</i> (Miki) D. Hartog (cỏ hệ tròn)	Cymodoceaceae	
<i>Zostera japonica</i> Asch. (cỏ lươn nhật)	Zosteraceae	+
<i>Ruppia maritima</i> L. (cỏ kim)	Ruppiceae	+

By the early 2000s, degradation had reached alarming levels—Ha Long Bay alone had lost around 70% of its seagrass cover, and Vietnam more than half since the 1970s—due to combined natural and anthropogenic pressures, including storms, sedimentation, destructive fishing, aquaculture expansion, urbanization, and pollution. Conservation action under the “Seagrass Charter” and the Convention on Biological Diversity was deemed crucial to halt losses, restore ecological balance, and promote sustainable coastal management.

#### 8.4. Foraminifer and Nannofossil Indicators in Ha Long and Bai Tu Long Bays

In recent years, foraminifera have attracted renewed scientific interest due to their high sensitivity to environ-

mental change and their valuable role as indicators in paleoenvironmental reconstruction and contemporary environmental studies [19,20].

Negri et al. [21] demonstrated that benthic foraminifera and calcareous nannofossils, when analyzed alongside their sedimentary context, are effective bioindicators of environmental quality, as they rapidly respond to stress and link physical sediment conditions with biological changes.

Sediments are mainly quartz- and clay-rich with traces of heavy minerals and biogenic coccoliths, reflecting both marine and terrestrial inputs, including coal-derived material from Quang Ninh’s mining areas.

A total of 46 foraminiferal taxa were recorded, showing a clear nearshore–offshore gradient. Offshore

sites, dominated by agglutinated taxa (e.g., *Lituolids*, *Trochammina*), indicate oxygenated, low-organic conditions, whereas nearshore assemblages are denser and richer, dominated by calcareous species such as *Ammonia tepida*, whose test deformities reveal tolerance to organic enrichment and stress.

Nannofossil assemblages, mainly *Gephyrocapsa oceanica*, *Reticulofenestra* spp., and *Emiliania huxleyi*, display similar spatial variability, with nearshore enrichment and reworked older forms indicating sediment recycling.

These patterns illustrate the coupling between sediment characteristics, nutrient input, and biological response. Nearshore zones benefit from organic input but risk eutrophication and oxygen depletion, while offshore areas remain stable but nutrient-limited. Foraminiferal deformities, particularly in *Ammonia* spp., serve as early-warning markers of pollution and hypoxia. Karstic lakes such as Ho Ca Hong lake act as natural sediment archives, recording anthropogenic inputs and long-term environmental shifts.

### 8.5. Zooplankton Assemblages and Environmental Dynamics in the Northern Coastal Waters of Vietnam

Plankton, and particularly the diversity and composition of zooplankton communities<sup>[22,23]</sup> play a pivotal role as bioindicators, providing sensitive and integrative signals of environmental change and ecosystem health in aquatic systems.

Zooplankton communities in the Quang Ninh–Hai Phong coastal region have been documented for over four decades, beginning with the Vietnam–China Gulf of Tonkin surveys (1959–1962) and followed by extensive studies through the 1970s–1990s in estuaries such as Ninh Co, Cua Day, and Ba Lat<sup>[24]</sup>. Since 1995, investigations have become integral to national biodiversity and environmental monitoring programs, revealing the ecological complexity of a system shaped by both continental and marine influences.

Thu (1998)<sup>[24]</sup> synthesized past efforts focusing on Co To, Bach Long Vi, and Long Chau, as well as estuarine contexts near Hai Phong, situating the Quang Ninh–Hai Phong findings within the wider Gulf of Tonkin context

(Table 10). Zooplankton diversity is moderate in species number (~200 species) but taxonomically broad, spanning seven phyla and 62 families. Copepods dominate, representing nearly 40% of recorded species, while freshwater taxa (e.g., Daphniidae) occur seasonally in estuarine and lagoonal zones. Species richness peaks around Cat Ba (115 taxa) and Bach Long Vi (101 taxa), declining toward inner estuaries such as Nam Trieu and Tien Yen (Tables 10 and 11).

Ecologically, assemblages are structured along a gradient from offshore to estuarine environments. Oceanic species are restricted to the outer islands, while broadly distributed oceanic forms—about one-fifth of total taxa—extend landward during the dry season. Coastal copepods form the dominant group (~40%), thriving in bays and estuaries under fluctuating salinity. Brackish-water species constitute 5–7% of total taxa, and wide-tolerance (*Oithona*, *Corycaeus*) and freshwater forms (10–15%) appear seasonally in nutrient-enriched lagoons. The prevalence of euryhaline copepods underscores the adaptive character of local communities.

Spatially, zooplankton abundance is highest in semi-enclosed, eutrophic systems such as Ha Long Bay and lowest in estuarine waters. A clear inverse trend links abundance and species richness: enclosed bays sustain dense populations dominated by few species, while open coastal waters maintain higher diversity but lower total abundance.

Seasonal patterns follow the monsoon regime. Abundance during the rainy season is roughly three times higher than in the dry season, reflecting enhanced nutrient inputs from freshwater inflow. Within estuaries, Nam Trieu shows the greatest densities and Tien Yen the lowest. These fluctuations highlight the role of seasonal hydrology in driving productivity and community structure.

Overall, zooplankton assemblages in the Quang Ninh–Hai Phong region mirror the strong environmental gradients from oceanic to estuarine systems. Their composition and dynamics make them effective indicators of hydrological variability and ecosystem condition in northern Vietnam’s coastal waters.

**Table 10.** Aggregated number of zooplankton taxa at sampled stations in the coastal waters of Hai Phong and Quang Ninh.

Marine Area	Number of Taxa	Sampling Frequency
Ha Long Bay	87	Multiple surveys/two seasons
Hang Trai – Dau Be	99	Multiple surveys/two seasons
Bai Tu Long	48	One survey/one season
Cat Ba	115	Multiple surveys/two seasons
Long Chau	79	Two surveys/two seasons
Co To	88	Two surveys/two seasons
Bach Long Vi	101	Two surveys/two seasons
Estuaries (Tien Yen, Nam Trieu, Ba Lat)	73	Two surveys/two seasons

**Table 11.** Distribution of the number of zooplankton taxa across taxonomic levels.

Phylum	Class	Subclass	Order	Family	Genus	Species
Rotatoria (Holoplankton)				2	2	2
Coelenterata (obsolete term; now Cnidaria) (both Holoplankton and Meroplankton)	1		3	3	6	7
Annelida (Meroplankton)	1		1	5		
Chaetognatha (Holoplankton)	1		1	1	2	7
Arthropoda (mainly zooplanktonic groups)	1	3	9	48	82	120
Protochordata (both Holoplankton and Meroplankton)	1			2	3	5
Mollusca (Meroplankton)	2		1	1	2	2
Others (larvae of fish, echinoderms, corals, etc.)			Unspecified			
Total	7	3	14	62	97	143

### 8.6. Overview of Zoobenthos Assemblages in Quang Ninh Coastal Area from Tra Co to Hai Phong

The zoobenthos accounts presented in this report are derived from analytical results and processed data from projects conducted in 2001–2003, as well as from benthic fauna surveys carried out continuously since 1993. **Tables 12 and 13** present aggregated data from surveys conducted between 1993 and 2003 <sup>[25]</sup>.

Extensive surveys conducted along the Quang Ninh–Hai Phong coast since 1993 reveal exceptionally rich and diverse benthic communities, reflecting the area’s complex hydrological and geomorphological conditions. A total of 1790 species have been identified, distributed among annelids (21%), mollusks (47.7%), crustaceans (23.2%), and echinoderms (8%) (**Table 12**). Polychaetes dominate the annelid group, while mollusks form the most diverse and economically valuable assemblage, particularly families such as Veneridae, Muricidae, and Mytilidae. Crustaceans—including penaeid shrimps, portunid and xanthid crabs, and squillid mantis shrimps—also contribute signifi-

cantly to the coastal economy. Echinoderms, though less diverse, play specialized ecological roles in benthic nutrient cycling.

Biodiversity levels are high throughout the Quang Ninh–Hai Phong sector, with Shannon Diversity Index ( $H'$ ) values between 2 and 3.7, indicating well-balanced ecosystems suitable for conservation. The richest benthic assemblages occur around Cat Ba (538 species) and Ha Long (532 species), followed by the Hai Phong tidal flats, while species richness declines progressively southward and toward offshore islands such as Tran and Bach Long Vi, where limited habitat heterogeneity constrains biodiversity.

Habitat diversity is the main determinant of species distribution. Sandy beaches support only sparse communities of mollusks and crustaceans, whereas tidal rocky reefs—particularly around Ha Long–Cat Ba—harbor the highest species richness, exceeding 250 species adapted to hard substrates and tidal exposure. Mangrove tidal flats sustain limited faunal communities dominated by gastropods and small crabs, constrained by sandy, nutrient-poor soils. The subtidal zones exhibit the greatest overall diversity, with more than 900 species recorded at Co To–Thanh

Lan and over 300 at Ha Long–Cat Ba, largely composed of mollusks, crustaceans, and polychaetes from key families such as Pinnidae, Muricidae, Portunidae, and Eunicidae.

Patterns of benthic biomass mirror this ecological gradient. Intertidal areas are far more productive than subtidal zones, with densities ranging from 268 to nearly 1000 individuals per square meter and biomass values up to 676 g/m<sup>2</sup>, compared with only a few tens of individuals and grams per square meter in subtidal habitats. Bach Long Vi

and Ba Mun islands register the highest intertidal biomass (up to 3000 g/m<sup>2</sup>), while deeper areas such as Co To Bay or Ha Mai show much lower productivity. Overall, the Quang Ninh–Hai Phong coast emerges as a biodiversity and productivity hotspot within northern Vietnam, where habitat heterogeneity, tidal dynamics, and nutrient inputs sustain some of the richest benthic ecosystems in the region. **Table 14** summarizes average densities, biomass, and diversity indices (H') across multiple bay and estuarine stations.

**Table 12.** Number of zoobenthos species and related descriptive statistics by phylum from Mong Cai (Quang Ninh) to Hai Van (Thua Thien–Hue Province).

Taxonomic Group	No. of Species	% of Total Species	No. of Families	Avg. no. of Species per Family	Dominant Classes/Families (Species Count)	Remarks
Annelida (Segmented worms)	378	21.0	46	8.2	Polychaeta: 372 spp.; Sipunculida: 6 spp.; Top families: <i>Eunicidae</i> (55), <i>Aphroditidae</i> (31), <i>Nereididae</i> (23)	High diversity; ecologically important; more than 50% of families have only 1–4 spp.
Mollusca (Mollusks)	856	47.7	120	7.13	Gastropoda: 449 spp.; Bivalvia: 368 spp.; Scaphopoda: 10 spp.; Cephalopoda: 19 spp.; Amphineura: 8 spp.; Top families: <i>Veneridae</i> (74), <i>Muricidae</i> (49), <i>Arcidae</i> (36), <i>Mytilidae</i> (32), <i>Tellinidae</i> (29), <i>Cerithiidae</i> (25)	Highest diversity; major group for fisheries and aquaculture
Crustacea (Crustaceans)	415	23.2	44	9.43	Top families: <i>Penaeidae</i> (40), <i>Portunidae</i> (37), <i>Xanthidae</i> (42), <i>Squillidae</i> (30)	Economically important; 7 families with 20–42 spp.; 30 families with less than 10 spp.
Echinodermata (Echinoderms)	144	8.0	39	3.7	Cucumariidae, Amphiuroidae, Ophiotrichidae (11–20 spp./family)	Lowest diversity; more than 50% of families have only 1–2 spp.
Total (All groups)	1790	100.0				Benthic fauna show high taxonomic and ecological diversity across northern Vietnam coast

**Table 13.** Number of zoobenthos species per phylum in coastal areas of Quang Ninh and Hai Phong. Shaded cells indicate data for comparison, from stations in Central Vietnam, outside the scope of this study.

Location	Mollusca	Crustacea	Annelida	Echinodermata	Total
Coastal zone Hai Phong – Quang Ninh	158	122	119	56	455
Hai Phong tidal zone (estuarine)	210	141	107		458
Tien Lang (estuarine)	33	20	16		69
Xuan Thuy (Ha Long bay)					44
Coastal zone Nghe An	123	5	3	2	133
Coastal zone Hue (HV–SC)	53	60	35	12	160
Tam Giang – Cau Hai					
Tran Island (offshore Quang Ninh)	55	13	3	5	76
Ba Mun (enclosed Cua Luc bay, Ha Long)	64	27	31	12	134
Co To – Thanh Lan (offshore Quang Ninh)	151	36	15	5	207
Ha Mai (Halong Bay)	127	39	79	10	255
Bach Long Vi (offshore Quang Ninh)	95	16	6	8	125
Cat Ba (Hai Phong)	193	116	124	8	538
Ha Long					532
Average (%)	60.45	18.2	16.5	5.03	100

**Table 14.** Density and zoobenthos biomass estimates at selected coastal sites in Quang Ninh and Hai Phong, with Sam Son (Thanh Hoa) and Cua Lo (Nghe An) included for comparison.

Location	Density (ind./m <sup>2</sup> )	Biomass (g/m <sup>2</sup> )	Diversity Index (H')
Tra Co (nearshore island)	200–260	3.8–374.9	2.845–4.469
Cua Luc (enclosed bay, Ha Long)	200–400	5.5–18.6	2.921–3.155
Do Son (nearshore)	180–260	8.7–110.8	2.947–3.927
Tien Lang (estuarine)	817–1552	–	1.370–1.812
Ba Lat (estuarine)	160–200	10.4–13.1	2.160–2.750
Sâm Sơn	300–400	6.8–9.7	1.556–2.913
Cửa Lò	100–220	4.9–89.5	1.921–2.321

### Zoobenthos Biodiversity in the Gulf of Tonkin: 2004 Assessment and Causes for Decline

Thung et al. [25] documented early signs of benthic biodiversity decline in the Gulf of Tonkin, where ecosystems once rich in species and economic value were already showing severe depletion by the early 2000s. Over half of the surveyed sites supported only one or two species, reflecting drastic losses of richness and biomass caused mainly by habitat degradation, overexploitation, and environmental stress. Iconic and commercially valuable species such as spiny lobsters (Palinuridae), abalone (*Haliotis diversicolor*), and pearl oysters had disappeared from major sites including Cat Ba, Co To, and Bach Long Vi, while clams (Veneridae), shrimps (Penaeidae), and crabs (Portunidae) had been heavily overharvested. Mollusks remained dominant, and echinoderms served as indicators of ecological stability, but diversity indices were generally low in estuarine and aquaculture-affected zones.

The case of Tien Lang District (Hai Phong) exemplified the human-driven causes of this decline. Once covering more than 4400 ha of tidal wetlands, the area was transformed through massive land reclamation, aquaculture expansion, and pollution from chemical fertilizers and pesticides. Unplanned aquaculture and destructive fishing methods further depleted native shrimp, crab, and fish populations, while mangrove forests shrank from about 794 ha to 300 ha between 1991 and 2004. These pressures caused the disappearance of ecologically and economically important species such as rays, seahorses, and cuttlefish, mirroring a broader pattern of unsustainable exploitation across the Gulf of Tonkin.

Despite these losses, Thung et al. [25] stressed that recovery remained possible through sustainable management and habitat restoration. They advocated spatial planning of

aquaculture zones, promotion of low-impact species such as mollusks and sea cucumbers, and the protection of sensitive ecosystems. Priority conservation areas were identified at the Co To–Thanh Lan Archipelago, Lan Ha Bay and southeastern Cat Ba, Ba Mun Island, and Bach Long Vi—key biodiversity hotspots whose protection is vital to reversing the downward trend and restoring benthic ecosystem resilience in northern Vietnam.

### 8.7. Sponge Assemblages of the Gulf of Tonkin

Marine sponges, owing to their high filtration capacity and sessile lifestyle, exhibit a strong bioaccumulation potential for trace elements and microplastics [26], making them effective bioindicators of microparticulate pollution in marine ecosystems [27].

Pansini et al. [28] observed that sponge research in Vietnam remained limited compared to other regions of the Eastern Sea. Out of the over 1500 sponge species known from the South China Sea region [29] 161 species have been recorded from Vietnam’s coasts, distributed among three classes: Hexactinellida (2 species, 2 families), Calcarea (6 species, 3 families), and Demospongiae (153 species, 36 families). However, more than 30% of the Vietnamese material stored in museum collections worldwide remains unidentified, reflecting the scarcity of taxonomic expertise and systematic surveys.

#### Sponge Assemblages in Halong Bay

The first systematic sponge survey in Ha Long Bay, carried out in April 2003 after a reconnaissance dive in 2002, marked a milestone in the study of the bay’s benthic fauna. Despite low visibility caused by suspended sediments, the shallow environment allowed adequate observation and collection, with the clearest conditions record-

ed in the enclosed Ang Du karstic lake. Nineteen species identified, revealing a rich and previously undocumented belonging exclusively to the class *Demospongiae* were sponge community (Table 15).

**Table 15.** List of sponge species and their families identified in the Vinh Ha Long (Ha Long Bay) area.

Family	Species	Record Status in Vietnam	Habitat/Locality	Distribution/Remarks
Tethyidae	<i>Tethya seychellensis</i> (HL34)	First record	Shallow, rocky, and sheltered areas of Ha Long Bay	Previously known from Indonesia; only two other <i>Tethya</i> species known from Vietnam ( <i>T. ingalli</i> , <i>T. japonica</i> )
Desmacelliidae	<i>Biemna cf. megalosigma</i> (HL9)	First record	-	Identified by large microscleres; differs from <i>B. fortis</i> ; known from Aru Islands, Indonesia
Suberitidae	<i>Plicatellopsis sp.</i> (HL31)	Probably new species	Ang Du karstic lake	Erect, branched (up to 40 cm), gold–green color due to symbiotic algae; resembles <i>P. arborescens</i>
Mycalidae	<i>Mycale plumosa</i> (HL47)	First record	Cong Island	Abundant; erect, cylindrical, anastomosing branches; distributed in Eastern Sea, King Island, Mergui Archipelago (Myanmar)
Axinellidae	<i>Acanthella hispida</i> (HL39)	First record	Ha Long Bay (attached to dead coral)	Second record globally (after Hong Kong); bright orange, wrinkled surface; related to <i>Stylissa carteri</i> and <i>Acanthrella pulcherrima</i>
Halichondriidae	<i>Amorphinopsis excavans</i> (HL26)	First record	Cavities of dead corals	Thickly encrusting; formerly in Clionidae; distributed in South China Sea, King Island, Mergui Archipelago, Indonesia
Niphatidae	<i>Gelliodes fibulata</i> (HL1)	Previously known (recorded in Nha Trang)	Coral reefs of Ha Long Bay	Erect, green-grey; Indo-Pacific distribution
Chalinidae	<i>Gellius sp.</i> (HL3)	Common species	On top of corals, often detached	Dark green due to symbiotic algae; similar to <i>Gellius varius var. fibrosa</i> (Sulawesi)
Chalinidae	<i>Haliclona spp.</i> (HL10, HL13, HL33, HL35)	Four undetermined species recorded	Ha Long Bay	76 <i>Haliclona spp.</i> known from South China Sea; only <i>H. clathrata</i> and <i>H. subarmigera</i> previously reported from Vietnam
Petrosiidae	<i>Xestospongia cf. testudinaria</i> (HL11)	First record	Ha Long Bay	Large barrel sponge; Indo-Pacific distribution (Indonesia, Singapore, Aru, Thailand, Nicobar, Andaman)
Petrosiidae	<i>Petrosia nigricans</i> (HL12)	First record	Ha Long Bay	Massive, dark grey, finger-like lobes; genus known in Vietnam by 4 other species; reported from Java
Dysideidae	<i>Dysidea cinerea</i> (HL8, HL21)	First record	-	Large, massive form; Indo–West Pacific distribution (Indonesia, Hong Kong)
Dysideidae	<i>Dysidea cf. fragilis</i> (HL6)	New regional record	-	Morphologically larger and darker than Atlantic specimens; distributed in Eastern Sea, Indonesia, Philippines, S and Central Vietnam
Irciniidae	<i>Ircinia echinata</i> (HL38)	First record	-	Massive, black, with conules connected by ridges; originally from Red Sea, now known from Eastern Sea and SE Indonesia

The survey recorded several new national occurrences and possible undescribed taxa. Among them, *Tethya seychellensis* represented the first Vietnamese record of this species, while *Plicatellopsis sp.* from Ang Du likely constitutes a new taxon. Other noteworthy additions include *Mycale plumosa*, *Amorphinopsis excavans*, *Xestospongia cf. testudinaria*, *Petrosia nigricans*, *Dysidea cinerea*, and *Ircinia echinata*, all newly reported for Vietnam. Most species are widely distributed across the Indo-Pacific and the

Eastern Sea region, indicating strong biogeographical connections between northern Vietnam and adjacent tropical seas.

Ecologically, many of these sponges—such as *Gellius sp.* and *Gelliodes fibulata*—are common components of coral reef assemblages, often associated with algae and other symbionts, suggesting productive benthic communities even in turbid waters. The findings highlight both the underexplored diversity of Ha Long Bay’s sponges and the

need for continued taxonomic and ecological investigations to refine species identification and understand their environmental significance.

### 8.8. Microalgae: Species Composition, Diversity, and Ecological Characteristics

The microalgal community of northern Vietnam’s coastal waters is taxonomically rich and ecologically versatile, dominated by diatoms and dinoflagellates that typify tropical–subtropical, euryhaline systems extending from estuaries to offshore zones [30]. A total of 494 species have been identified, belonging to 140 genera, 45 families, 14 orders, and 7 classes. Diatoms (*Bacillariophyceae*) comprise 276 species (55.9%), dinoflagellates (*Dinophyceae*) 169 species (34.2%), followed by green algae (5.3%), blue-green algae (2.6%), and minor groups of euglenoids, golden, and silicoflagellates. Dominant genera include *Chaetoceros*, *Coscinodiscus*, *Rhizosolenia*, *Navicula*, and *Biddulphia* among diatoms, and *Protoperidinium*, *Ceratium*, and *Prorocentrum* among dinoflagellates. Freshwater

and brackish taxa such as *Pediastrum*, *Scenedesmus*, *Oscillatoria*, and *Anabaena* appear mainly near estuaries during the rainy season (Table 16).

Ecologically, the assemblage is structured into five main groups reflecting salinity tolerance and habitat preference. (1) Coastal and brackish species (*Coscinodiscus jonesianus*, *Chaetoceros affinis*) thrive in nutrient-rich nearshore waters; (2) Neritic species (*Rhizosolenia bergonii*, *Chaetoceros peruvianus*) characterize transitional offshore–brackish zones; (3) Oceanic and cosmopolitan taxa (*Thalassiosira nitzschoides*, *Ceratium furca*, *Prorocentrum micans*) dominate offshore oligotrophic environments; (4) Freshwater and estuarine intrusions (*Pediastrum*, *Anabaena*, *Euglena*) occur seasonally with high river discharge; and (5) Opportunistic and widely distributed species (*Skeletonema costatum*, *Nitzschia* spp.) proliferate under eutrophic or disturbed conditions. This composition reflects both natural hydrochemical gradients and anthropogenic enrichment, highlighting a resilient yet sensitive coastal phytoplankton community (Table 17).

**Table 16.** Composition of microalgal taxonomic groups and dominant genera in Ha Long and Bai Tu Long Bays.

Class	No. of Orders	No. of Families	No. of Genera	No. of Species	% of Total Species	Dominant/Representative Genera
Bacillariophyceae (Diatoms)	2	19	73	276	55.9	<i>Chaetoceros</i> (47 spp.), <i>Coscinodiscus</i> (20), <i>Rhizosolenia</i> (18), <i>Navicula</i> (14), <i>Biddulphia</i> (20), <i>Melosira</i> (10), <i>Surirella</i> (11), <i>Bacteriastrum</i> (10)
Dinophyceae (Dinoflagellates)	4	14	42	169	34.2	<i>Protoperidinium</i> (37 spp.), <i>Ceratium</i> (31), <i>Prorocentrum</i> (13), <i>Dinophysis</i> (11), <i>Alexandrium</i> (10)
Chrysophyceae (Golden algae)	1	1	1	1	0.2	—
Dictyochophyceae	1	2	4	5	1	—
Cyanophyceae (Blue-green algae)	1	2	7	13	2.6	<i>Oscillatoria</i> , <i>Lyngbya</i> , <i>Spirulina</i> , <i>Anabaena</i>
Chlorophyceae (Green algae)	3	6	9	26	5.3	<i>Pediastrum</i> , <i>Scenedesmus</i>
Euglenophyceae	1	1	4	4	0.8	—
<b>Total</b>	<b>14</b>	<b>45</b>	<b>140</b>	<b>494</b>	<b>100</b>	—

**Table 17.** Microalgal assemblage composition under different ecological conditions in Ha Long and Bai Tu Long Bays.

Ecological Group	Representative Species/Genera	Ecological Notes
Coastal and brackish-water species	<i>Coscinodiscus jonesianus</i> , <i>C. jonesianus</i> var. <i>communita</i> , <i>Bacteriastrum hyalinum</i> , <i>Guinardia striata</i> , <i>Chaetoceros affinis</i> , <i>Ch. curvisetus</i> , <i>Ch. constrictus</i> , <i>Dactyliosolen mediterraneus</i> , <i>Eucampia cornuta</i>	Typical of shallow coastal and estuarine zones; tolerant of fluctuating salinity and nutrient-rich environments.

Table 17. Cont.

Ecological Group	Representative Species/Genera	Ecological Notes
Neritic (offshore–brackish transition) species	<i>Bacteriastrum comosum</i> , <i>Rhizosolenia bergonii</i> , <i>Rh. robusta</i> , <i>Pseudosolenia calcar-avis</i> , <i>Chaetoceros peruvianus</i> , <i>Pyrophacus horologicum</i>	Adapted to intermediate salinity waters between nearshore and oceanic zones.
Oceanic and cosmopolitan species	<i>Coscinodiscus radiatus</i> , <i>C. excentricus</i> , <i>Asteromphalus cleveanus</i> , <i>Thalassiosira nitzschioides</i> , <i>Dinophysis caudata</i> , <i>Proocentrum micans</i> , <i>Ceratium furca</i> , <i>C. fusus</i> , <i>Protoperidinium oceanicum</i>	Widespread species found in open waters; many have cosmopolitan distribution patterns.
Freshwater and estuarine intrusions	Green algae ( <i>Pediastrum</i> , <i>Scenedesmus</i> , <i>Cosmarium</i> , <i>Staurastrum</i> ), blue-green algae ( <i>Oscillatoria</i> , <i>Lyngbya</i> , <i>Spirulina</i> , <i>Anabaena</i> ), euglenoids ( <i>Euglena</i> , <i>Phacus</i> )	Enter coastal waters mainly during rainy season via river discharge and estuarine mixing.
Widely distributed and opportunistic species	<i>Proboscia alata</i> , <i>Chaetoceros compressus</i> , <i>Skeletonema costatum</i> , <i>Chaetoceros anastomosans</i> , <i>Bacteriastrum hyalinum</i> , <i>Gyrosigma balticum</i> , <i>Nitzschia sp.</i> , <i>Bacillaria paradoxa</i> , <i>Surirella ovalis</i> , <i>Campylodiscus celnensis</i>	Euryhaline and resilient taxa occurring from estuaries to nearshore zones; indicators of dynamic, nutrient-rich environments.

### 8.8.1. Spatial Distribution of Microalgal Density

Microalgal abundance varies widely by site, season, and depth, ranging from 10<sup>2</sup> to over 10<sup>5</sup> cells/L. Diatoms dominate throughout, while dinoflagellates, green, and blue-green algae occur sporadically (Table 18).

- Ha Mai: 2.0–3.1 × 10<sup>4</sup> cells/L; bottom layers richer; dominants *Thalassiosira*, *Chaetoceros curvisetus*, *Thalassionema nitzschioides*.
- Ba Mun: up to >10<sup>5</sup> cells/L; *Skeletonema costatum* prevailing (60–70%); *Nitzschia* and *Thalassionema* elsewhere.
- Tien Yen–Ha Coi: 3.0–4.0 × 10<sup>4</sup> cells/L; *Chaetoceros* and *Thalassionema* dominant, reaching 5.1 × 10<sup>4</sup> at some stations.
- Thanh Lan: 5.0–7.0 × 10<sup>5</sup> cells/L, highest recorded; *Bacteriastrum varians* dominant with *Chaetoceros*,

*Leptocylindrus*, *Rhizosolenia*.

- Co To: 10<sup>2</sup>–5.1 × 10<sup>4</sup> cells/L; *Chaetoceros*, *Bacteriastrum*, and *Thalassionema* prevail; densities increase in rainy season.
- Ha Long Bay: typically, >10<sup>5</sup> cells/L in dry season; *Rhizosolenia cylindrus*, *Pseudonitzschia*, *Chaetoceros compressus*, *Leptocylindrus danicus*; higher at surface layers.
- Tran Island: lower (~1.6 × 10<sup>3</sup>); *Chaetoceros* and *Ceratium fusus* dominate, with upwelling-related blooms in May.

Overall, Thanh Lan, Ba Mun, and Ha Long Bay show the highest phytoplankton densities, while Ha Mai, Tien Yen–Ha Coi, Co To, and Tran Island display moderate levels. Seasonal peaks correspond to the rainy season, when freshwater inflow enhances nutrient availability, confirming hydrological and nutrient control as the main drivers of microalgal productivity in the region.

Table 18. Spatial distribution, vertical and seasonal patterns of microalgal densities across different ecological conditions in Hạ Long and Bai Tu Long Bays.

Site/Area	Density Range (cells/L)	Vertical/Seasonal Pattern	Dominant/Notable Taxa	Ecological Notes
Ha Mai	2.0 × 10 <sup>4</sup> –3.1 × 10 <sup>4</sup>	Bottom layers richer than surface	<i>Thalassiosira</i> , <i>Chaetoceros</i> ( <i>Ch. curvisetus</i> , <i>Ch. pseudocurvisetus</i> , <i>Ch. lorenzianus</i> ), <i>Nitzschia</i> , <i>Thalassionema nitzschioides</i> , <i>Lauderia borealis</i> , <i>Leptocylindrus danicus</i> , <i>Pleurosigma naviculaceum</i> , <i>Eucampia zoodiacus</i>	Moderate density; typical coastal assemblage dominated by diatoms.
Ba Mun	2.0 × 10 <sup>4</sup> –>10 <sup>5</sup>	Uneven among stations; high peaks (>10 <sup>5</sup> ) at some sites	<i>Skeletonema costatum</i> (60–70%), <i>Nitzschia</i> (~10%), <i>Thalassionema</i>	Extremely high at Station VI; diatom dominance; indicative of nutrient-rich waters.
Tien Yen–Ha Coi	3.0 × 10 <sup>4</sup> –5.1 × 10 <sup>4</sup>	Relatively uniform in Sept 2002; higher variability in May 2003	<i>Chaetoceros</i> , <i>Thalassionema nitzschioides</i> , <i>Pseudonitzschia</i>	Coastal estuarine zone; moderate densities; seasonal fluctuations.

Table 18. Cont.

Site/Area	Density Range (cells/L)	Vertical/Seasonal Pattern	Dominant/Notable Taxa	Ecological Notes
Thanh Lan	$5.0 \times 10^5$ – $7.0 \times 10^5$	Little difference between surface and bottom	<i>Bacteriastrum varians</i> , <i>Chaetoceros</i> , <i>Leptocylindrus danicus</i> , <i>Rhizosolenia</i> , <i>Nitzschia</i>	One of the densest sites; uniform vertical structure; high productivity.
Co To	$3.0 \times 10^2$ – $5.1 \times 10^4$ (dry); up to $10^5$ (rainy)	Rainy season densities higher; dominants shift seasonally	<i>Chaetoceros lorenzianus</i> , <i>Bacteriastrum comosum</i> , <i>Ch. diversus</i> , <i>Bacteriastrum hyalinum</i> , <i>Thalassionema frauenfeldii</i> , <i>Rhizosolenia cylindrus</i> , <i>Thalassiosira</i> , <i>Skeletonema</i> , <i>Nitzschia</i>	Highly variable spatially and seasonally; estuarine–marine transitional character.
Ha Long Bay	$1.0 \times 10^4$ – $10^5$	Surface layers often higher; exceptions at some stations	<i>Rhizosolenia cylindrus</i> , <i>Pseudonitzschia</i> , <i>Chaetoceros curvisetus</i> , <i>Ch. compressus</i> , <i>Leptocylindrus danicus</i>	Consistently high densities; dry season peaks; diatom-dominated community.
Tran Island	$\sim 1.6 \times 10^3$ (up to $10^4$ during upwelling)	Peaks up to $10^4$ during upwelling (May)	<i>Chaetoceros</i> (up to $2.7 \times 10^3$ ), <i>Ceratium fusus</i> , <i>Biddulphia regia</i>	Lower average density; influenced by upwelling dynamics; mixed diatom–dinoflagellate assemblages.

### 8.8.2. Benthic Dinoflagellates Associated with Coral Reefs

Surveys of benthic dinoflagellates around the coral reefs of Long Chau, Co To, Thanh Lan, Thuong Mai, North Co To, North Thanh Lan, and Hon Ca Chep revealed moderate species richness but large spatial differences in abundance. Densities ranged from 31 to 2272 cells/g, peaking at Hon Ca Chep where *Ostreopsis ovata* accounted for ~96% of total cells (2177 cells/g). Long Chau showed moderate densities (~75 cells/g) dominated by *O. ovata* and *Coolia monotis*, while North Thanh Lan had the lowest (31 cells/g). Intermediate values occurred at Hong Van (356 cells/g) and North Co To (157 cells/g), where *Prorocentrum mexicanum* reached up to 267 cells/g.

### 8.9. Historical Account on Coral Reefs in Quang Ninh–Northern Vietnam

Northern Vietnam’s coastal zone hosts two principal reef types: fringing reefs, widely developed around offshore islands such as Bach Long Vi, Co To, and the Ha Long–Cat Ba area, and smaller patch reefs scattered across Ha Long Bay, Cat Ba, Ba Mun, Hon Me, and Tran Islands [31]. Hard corals (*Scleractinia*) were long recognized as key structural and ecological components of these marine systems, often compared to tropical rainforests for their biodiversity and productivity. Systematic research began only in the mid-1980s under national and international initiatives, and by the late 1990s the first comprehensive baselines on reef composition, degradation, and conservation needs had been established (Tables 19 and 20).

Table 19. Number and proportion of hard coral species in different segments of the Quang Ninh coastal tract.

Taxonomic Level	Group	Number of Species	Notes
Overall	Total species	199	57 genera, 14 families
Overall	Share of Vietnam’s total	53.2% species, 71.2% genera, 82.3% families	
Families	Acroporidae	49	Most species-rich family
Families	Faviidae	47	
Families	Poritidae	20	
Families	Fungiidae	13	
Families	Subtotal	129 (66.5%)	Together, two-thirds of total species
Genera	Acropora	31	Most species-rich genus
Genera	Montipora	16	
Genera	Porites	12	
Genera	Favia	10	
Genera	Favites	8	
Genera	Fungia	7	
Genera	Goniopora	7	
Genera	Turbinaria	7	
Genera	Nearly 30 other genera	1–2 each	Low representation

**Table 20.** Number and proportion of coral species in different segments of the Quang Ninh coastal tract (except, Hai Van- Son Cha, in Thua Thien Hue and Con Co island in Quang Tri, Central Vietnam).

Site	Number of Species	Percentage of Total (%)
Ha Long–Cat Ba	152	76.4
Hai Van–Son Cha	129	64.8
Long Chau Archipelago	122	61.3
Co To Archipelago	103	51.8
Bach Long Vi Island	99	49.7
Thuong Mai & Ha Mai Islands	91	45.7
Con Co Island	73	36.7
Ba Mun Island	71	35.7
Tran Island	42	21.1

Early inventories recorded 199 species of hard corals belonging to 57 genera and 14 families—representing more than half of Vietnam’s known coral diversity. The assemblage was dominated by the families Acroporidae, Faviidae, Poritidae, and Fungiidae<sup>[31]</sup>. Surveys conducted in 2002–2003 around the Ha Long–Cat Ba locale documented a reduced assemblage of 107 species from 35 genera and 11 families (**Table 21**), with dominance shifting toward the Faviidae, followed by Acroporidae, Fungiidae, Pectiniidae, and Poritidae—an indication of spatial variation and progressive ecological stress.

Coral distribution exhibits marked spatial and environmental gradients. The Ha Long–Cat Ba area remains the richest, hosting over 150 species (about 76% of the northern total), followed by Hai Van–Son Cha, Long Chau, and Co To, while Tran Island supports the fewest species. Habitat complexity and geomorphological diversity are decisive: the intricate coastal and island topography of Ha Long–Cat Ba favors reef development, whereas freshwater inflows and confined channels constrain nearshore growth, concentrating coral cover offshore. Among these, Bach

Long Vi supports more diverse reefs than Tran Island due to clearer water and deeper seabeds. Vertical distribution is limited by turbidity and tidal amplitude, with most reefs restricted to shallow depths—from about +0.5 m above mean high water to 6–7 m around Cat Ba and 4–5 m in Ha Long Bay.

Live coral cover, as recorded in the late 1990s, varied widely among sites: 5–65% in Ha Long Bay (average 32%), 2.6–94% in Bach Long Vi (average 31%), and up to 50–51% at Co To and Hai Van–Son Cha. Yet by the early 2000s, coral degradation had intensified. In the Ha Long–Cat Ba region, live cover declined sharply—over 85% loss in Cong Do and Ang Tham, and nearly half at Cong La and Ba Trai Dao, where dead coral rubble now predominates (**Table 22**). Community composition shifted from fragile *Acropora* species toward more resilient taxa such as *Galaxea*, reflecting adaptation to increasingly disturbed conditions. Some offshore sites, including Dau Be, Hang Trai, and Cong Hip, retained relatively high vitality, with live cover exceeding 50–75%.

**Table 21.** Changes in coral species and genera richness at selected reefs in the Vinh Ha Long (Ha Long Bay) and Cat Ba area (Hai Phong) (pre-1998 vs. 2003).

Survey Period	Species	Genera	Families	Dominant Families (% of Species)	Key Dominant Genera
Late 1990s (northern coastal waters, including Ha Long–Cat Ba)	199	57	14	Acroporidae, Faviidae, Poritidae, Fungiidae (≈ 2/3 of species)	Acropora, Montipora, Porites, Favia, Favites, Fungia, Goniopora, Turbinaria
2002–2003 (Ha Long–Cat Ba focus) <sup>[31]</sup>	107	35	11	Faviidae (30.8%), Acroporidae (16.8%), Fungiidae (11.2%), Pectiniidae (10.3%), Poritidae (9.3%)	Favia, Favites, Acropora, Porites; minor representation of Agariciidae, Mussidae, Merulinidae, etc.

**Table 22.** Changes in coral species richness and live coral cover, with percentage decline, at selected reef sites in Vinh Ha Long (Ha Long Bay) and Cat Ba (Hai Phong) (pre-1998 vs. 2003).

Reef Location	Species Number before 1998	Species Number in 2003	Decline (%)	Live Coral Cover before 1998	Live Coral Cover in 2003	Decline (%)
Cong Lá	73	39	46.6	29.3	17	42
Áng Thắm	49	16	67.3	55.7	7.4	86.7
Ba Trái Đảo	59	29	50.8	85.7	44.6	48
Vạn Bội		31			31.1	
Hang Trai	78	22	71.8	78.1	65	16.8
Công Híp	46	40	13.0		75.4	
Công Đò	51	27	47.1	28.3	1	96.5
Tùng Ngón	75	29	61.3	64.7	48	25.8
Cọc Chèo	58	48	17.2	68.4	55.9	18.3

Overall, coral reefs in northern Vietnam illustrate a clear gradient of ecological richness and decline—from diverse, structurally complex systems in the late twentieth century to increasingly fragmented and stress-tolerant communities in the early 2000s.

#### Emerging Threats

By the late 1990s, coral reefs in northern Vietnam were already experiencing severe stress from combined natural and anthropogenic pressures. Increased river discharge, coal mining, industrial pollution, and deforestation intensified sedimentation and turbidity, reducing both the areal extent and depth range of coral growth. Reefs that once reached depths of 10–12 m had, by the early 2000s, retreated to 6–7 m, reflecting significant habitat loss and diminished biodiversity.

Episodes of mass mortality in Ha Long–Cat Ba between 1998 and 2000, the collapse of reefs at Hon Me (Thanh Hoa Province), and chronic degradation at Bach Long Vi underscored this vulnerability. Follow-up surveys in 2002–2003 revealed a sharp contraction in species richness and a shift in dominance from the sensitive *Acroporidae* to the more resilient *Faviidae*. Within less than a decade, the coral community had become markedly simplified and homogenized, signaling an ecological transition from complex, diverse systems to stress-tolerant assemblages.

As early as 1996, Yet and Lang<sup>[31]</sup> warned that without effective management and mitigation of developmental pressures, the coral reefs of the Ha Long–Cat Ba region were facing an imminent risk of functional collapse and potential extinction.

## 9. Summary, Conclusions and Recommendations

### 9.1. Key Findings from the Review

The review demonstrates that the Quang Ninh–Hai Phong coastal system represents both a biodiversity stronghold and an area of intense anthropogenic transformation. The early 2000s baseline established by the Vietnam–Italy cooperation project remains an indispensable reference for tracking ecological change, showing that many critical ecosystems—mangroves, seagrasses, coral reefs, and benthic communities—had already entered a phase of decline due to expanding aquaculture, port development, industrial discharge, and coastal urbanization.

Quantitative data reveal that nitrogen and phosphate concentrations increased significantly between 1996 and 2000, oil and heavy metal pollution became chronic, and organochlorine residues persisted despite their ban. Coral reefs lost over half of their live cover within less than a decade, with sensitive *Acroporidae* replaced by resilient but less diverse *Faviidae* assemblages. Mangrove and seagrass habitats were reduced by more than two thirds, while benthic biodiversity and biomass contracted sharply in estuarine zones.

Despite these pressures, the Hai Phong–Quang Ninh system retains high ecological potential: coral, zoobenthos, and plankton diversity remain among the highest in the Gulf of Tonkin, and the region continues to support vital ecosystem services. However, the study underscores that conservation responses have lagged behind development,

and monitoring has been fragmented, constraining the capacity to detect trends and manage cumulative impacts.

The key insight emerging from the review is that sustainable management of this World Heritage coastal complex requires a quantified understanding of change. Environmental sustainability and socio-economic viability can only be achieved when system trajectories are measured against a consistent reference point—allowing managers to attribute causes, evaluate severity, and adjust policy responses accordingly.

## 9.2. Proposed Indicator Set for Long-Term Monitoring

Based on the DPSIR framework<sup>[32,33]</sup> and international practice (UNEP, EU Marine Strategy Framework Directive<sup>[34]</sup>, UNESCO WHC guidelines<sup>[35]</sup>), a core indicator suite is proposed for the long-term monitoring of environmental health and heritage values in the Quang Ninh–Hai Phong coastal system. Indicators are grouped by domain and designed to capture pressures, state, and responses in an integrated manner.

### 9.2.1. Water and Sediment Quality

- Nutrient concentrations ( $\text{NH}_4^+$ ,  $\text{NO}_2^-$ ,  $\text{PO}_4^{3-}$ )—eutrophication risk.
- Oil and petroleum hydrocarbons—shipping and industrial pressure.
- Heavy metals (Cd, Hg, Zn, Cu)—chronic land-derived contamination.
- Organochlorine pesticides—persistent pollutants and legacy contamination from agriculture.
- Total suspended solids (TSS)—sediment stress from rivers' suspended load on coral and seagrass.
- pH, salinity, and dissolved oxygen—baseline physico-chemical parameters.

### 9.2.2. Biodiversity and Habitat Integrity

- Coral species richness and live cover (%) by family.
- Seagrass extent (acreage in hectares) and species assemblages composition.
- Mangrove and intertidal wetland forest extent (acreage in hectares), species composition, and regenera-

tion rates.

- Zoobenthos and zooplankton species richness and Shannon diversity ( $H'$ ).
- Sponge and foraminiferal assemblages as bioindicators of water quality.

### 9.2.3. Ecosystem Function and Productivity

- Benthic biomass and abundance ( $\text{g}/\text{m}^2$ ,  $\text{ind.}/\text{m}^2$ ).
- Fishery catch per unit effort (CPUE) and spawning stock biomass.
- Chlorophyll-a concentration (primary productivity proxy).

### 9.2.4. Socio-Economic and Governance Indicators

- Aquaculture area and yield per hectare.
- Port throughput and maritime traffic density.
- Tourism visitation and carrying capacity utilization.
- Implementation rate of environmental impact assessments (EIAs) and heritage monitoring reports.

Together, these indicators form an operational monitoring matrix linking ecological status with socio-economic drivers and policy responses. Periodic data collection at fixed reference sites (e.g., Ha Long Bay, Cat Ba, Bach Dang, Ba Lat, Co To) would enable trend analysis and support reporting under UNESCO's Periodic Reporting and Sustainable Development Goals (SDG 14, 15).

## 9.3. Policy and Management Recommendations

- Institutionalize the baseline: Adopt the 1995–2004 period as the formal environmental reference for the Ha Long–Cat Ba World Heritage complex. This should underpin all environmental, tourism, and spatial planning assessments.
- Integrate monitoring with Marine Spatial Planning (MSP) and ICZM: Link indicator-based monitoring with existing planning instruments under MONRE and provincial authorities to guide zoning, port expansion, aquaculture, and tourism development.
- Reinforce pollution control and ecosystem restoration: for example, by strengthening wastewater

treatment and industrial discharge monitoring in the Bach Dang and Ba Lat estuaries; by restoring mangrove and seagrass ecosystems as natural filters and carbon sinks; by prioritizing coral reef rehabilitation and control sediment runoff from mining and construction.

- Promote adaptive, evidence-based management: Establish a data-sharing platform between ISTE, and provincial departments to ensure that scientific findings directly inform management decisions.
- Strengthen heritage–development balance: for example, by applying carrying-capacity assessments for tourism and aquaculture; by ensuring that UNESCO and Biosphere Reserve obligations are embedded in local economic planning; by introducing environmental compensation and green certification for enterprises operating within or near the heritage buffer zone.
- Enhance community participation: Encourage co-management and citizen science initiatives to increase awareness and local stewardship, particularly in mangrove and coral reef restoration projects.

#### **9.4. Pathways for Future Research and Regional Cooperation**

- Reconstructing historical baselines: Develop multiproxy reconstructions (sediment cores, archival imagery, oral histories) to refine pre-2000 reference conditions and extend the temporal understanding of ecosystem change.
- Climate change and resilience modelling: Assess the combined impacts of sea-level rise, salinity intrusion, and storm surges on karstic and island ecosystems, identifying resilience thresholds and adaptation strategies.
- Integrated indicator observatories: Establish a long-term coastal observatory network connecting Hai Phong, Quang Ninh, and regional partners (e.g., Thua Thien Hue, Quang Tri, Guangxi, Hainan) for comparative monitoring across the Gulf of Tonkin.
- Heritage-linked blue economy research: Explore how low-impact tourism, sustainable aquaculture,

and cultural landscape valorization can be synergized to deliver both conservation and economic benefits.

- Transboundary and international collaboration: Strengthen data harmonization and exchange within the framework of the UNEP Regional Seas Programme and UNESCO’s World Heritage Marine Programme, enabling cross-site learning and joint capacity building.

In conclusion, the long-term sustainability of the Ha Long–Cat Ba–Quang Ninh–Hai Phong coastal complex depends on transforming existing knowledge into a continuous, indicator-based management system. Only through measurable baselines, coordinated governance, and sustained international cooperation can this emblematic World Heritage region evolve toward a truly integrated model of conservation and development.

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### **Institutional Review Board Statement**

Not applicable.

### **Informed Consent Statement**

Not applicable.

### **Data Availability Statement**

Data supporting the reported results are held in non-public institutional archives and are unavailable due to institutional access restrictions.

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## Conflicts of Interest

The authors declare that they have no financial, institutional, or personal conflicts of interest that could have influenced the conduct, analysis, or interpretation of this research. The study was carried out in the spirit of academic collaboration and a shared commitment to the sustainable management and conservation of Vietnam's coastal and World Heritage environments.

## References

- [1] Cong, N.V., Thanh, T.D., Nhon, D.H., 2020. Integrated coastal zone management in Vietnam—status and emerging problems. *Vietnam Journal of Marine Science and Technology*. 20(4), 369–381. DOI: <https://doi.org/10.15625/1859-3097/15316>
- [2] Chandrasekharan, B.D., Dinh, Q.T., Horansky, C.E., et al., 2022. *Situation Assessment of Integrated Coastal Zone Management (ICZM) in Vietnam*. World Bank Group: Washington, DC, USA. Available from: <http://documents.worldbank.org/curated/en/099731006282211089>
- [3] Son, N.M., Lien, N.T.V., Thu, H.T.Y., 2025. *Training Materials on Marine Spatial Planning and Integrated Coastal Zone Management in Vietnam*. UNDP Vietnam Publications: Hanoi, Vietnam. p. 147. (in Vietnamese)
- [4] IPBES, 2019. *Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. IPBES Secretariat: Bonn, Germany. p. 1700.
- [5] O'Brien, K. (Ed.), 2000. *Developing Strategies for Climate Change: The UNEP Country Studies on Climate Change Impacts and Adaptations Assessment*. CICERO & UNEP: Oslo, Norway.
- [6] International Union for Conservation of Nature and Natural Resources (IUCN), United Nations Environment Programme (UNEP), World Wildlife Fund (WWF), 1980. *World Conservation Strategy: Living Resource Conservation for Sustainable Development*. International Union for Conservation of Nature and Natural Resources: Gland, Switzerland.
- [7] International Union for Conservation of Nature and Natural Resources (IUCN), United Nations Environment Programme (UNEP), World Wildlife Fund (WWF), 1991. *Caring for the Earth: A Strategy for Sustainable Living*. International Union for Conservation of Nature and Natural Resources: Gland, Switzerland.
- [8] WWF Vietnam Marine Conservation Northern Survey Team, 1993. *Survey Report on the Biodiversity, Resource Utilization, and Conservation Potential of Cat Ba Region, Northern Vietnam*. World Wide Fund for Nature (WWF): Gland, Switzerland.
- [9] WWF Vietnam Marine Conservation Northern Survey Team, 1994. *Survey Report on the Biodiversity, Resource Utilization, and Conservation Potential of Co To Island, Quang Ninh, Northern Vietnam*. World Wide Fund for Nature (WWF): Gland, Switzerland.
- [10] Vinh, L.D., Tri, N.M., 2024. Human development in Vietnam: A systematic review. *International Journal of Sustainable Development and Planning*. 19(8), 3117–3128. DOI: <https://doi.org/10.18280/ijstdp.190825>
- [11] An, D., 2006. *Vietnam Economy 2001–2005 and Socio-Economic Development Plan 2006–2010*. East Asian Bureau of Economic Research: Canberra, Australia.
- [12] Anh, P.V., 2025. Vietnam's economic transformation: Successes, challenges, and strategies for sustainable growth. *Intergovernmental Research and Policy Journal*. Available from: <https://irpj.euclid.int/articles/vietnams-economic-transformation-successes-challenges-and-strategies-for-sustainable-growth/>
- [13] Le, P.V., Luong, T.N., Khanh, Q.N., 2025. An overview of financial subsidy programs in Vietnamese fisheries during the past 25 years: An evaluation and recommendations towards improved future mechanisms. *World Development Perspectives*. 39, 100704. DOI: <https://doi.org/10.1016/j.wdp.2025.100704>

- [14] Dieu, L.V., 2002. Assessment of environmental conditions in the northern coastal waters of Vietnam. In: Thung, D.C., Sarti, M. (Eds.). *Biodiversity Conservation in the Coastal Areas of Vietnam*. Vietnam National University Publishing House: Hanoi, Vietnam. pp. 37–50. (in Vietnamese)
- [15] Ha, N.T., Pham, T.D., Tran, T.T.H., 2021. Zoning seagrass protection in Lap An Lagoon, Vietnam using a novel integrated framework for sustainable coastal management. *Wetlands*. 41, 122. DOI: <https://doi.org/10.1007/s13157-021-01504-8>
- [16] Losciale, R., Day, J., Heron, S., 2022. Conservation status, research, and knowledge of seagrass habitats in World Heritage properties. *Conservation Science and Practice*. 4(12), e12830. DOI: <https://doi.org/10.1111/csp2.12830>
- [17] Tien, N.V., 1998. Seagrass resources in Quang Ninh province waters. In *Marine Biology, Resources, Ecology and Environment*. VAST Science and Technology Publishing House: Hanoi, Vietnam. pp. 960–966. (in Vietnamese)
- [18] Tien, N.V., 1999. Data on seagrass species composition and distribution in Vietnam. In: Chu Hoi, N., Yet, N.V., Tien, N.V., et al. (Eds.). *Marine Resources and Environment*. 6, 192–206. VAST Science and Technology Publishing House: Hanoi, Vietnam. (in Vietnamese)
- [19] Naik, G.R., Kulkarni, M.N., Indap, M.M., 2023. Understanding role of foraminifera in environmental studies: A review. *International Journal of Ecology and Environmental Sciences*. 49, 457–471.
- [20] O'Brien, P.A.J., Asteman, I.P., Bouchet, V.M.P., 2021. Benthic foraminiferal indices and environmental quality assessment of transitional waters: A review of current challenges and future research perspectives. *Water*. 13(14), 1898. DOI: <https://doi.org/10.3390/w13141898>
- [21] Negri, A., Thung, D.C., Morigi, C., et al., 2018. Ha Long Bay (Vietnam) sediment and microfaunal background assessment for future monitoring actions. In: Anderle, M. (Ed.). *Innovations in Land, Water and Energy for Vietnam's Sustainable Development*. Springer: Cham, Switzerland. DOI: [https://doi.org/10.1007/978-3-030-51260-6\\_3](https://doi.org/10.1007/978-3-030-51260-6_3)
- [22] Chandel, P., Mahajan, D., Thakur, K., et al., 2023. A review on plankton as a bioindicator: A promising tool for monitoring water quality. *World Water Policy*. 10(1), 213–232. DOI: <https://doi.org/10.1002/wwp2.12137>
- [23] Goździewicz, A.M., Cymes, I., Glińska-Lewczuk, K., 2024. Zooplankton functional diversity as a bioindicator of freshwater ecosystem health across land use gradient. *Scientific Reports*. 14, 18456. DOI: <https://doi.org/10.1038/s41598-024-69577-z>
- [24] Thu, N.V., 1998. Zooplankton in the Cat Ba–Ha Long coastal waters. In: Chu Hoi, N., Yet, N.V., Tien, N.V., et al. (Eds.). *Marine Environmental Resources*. VAST Science and Technology Publishing House: Hanoi, Vietnam. pp. 167–175. (in Vietnamese)
- [25] Thung, D.C., Thuy, L.T., Dung, L.Q., 2004. Biodiversity of benthic animals along the coastal zone from Tra Co to north of Hai Van Pass. In: Thung, D.C., Sarti, M. (Eds.). *Conservation of Biodiversity in Vietnam's Coastal Zone*. Vietnam National University Publishing House: Hanoi, Vietnam. pp. 160–178. (in Vietnamese)
- [26] Sivan, G., Dileep, V., Yesudas, A., et al., 2025. Comparative bioaccumulation potential of trace elements and microplastics in marine sponges as bioindicators. *International Journal of Environmental Research*. 19, 255. DOI: <https://doi.org/10.1007/s41742-025-00930-4>
- [27] Girard, E.B., Fuchs, A., Kaliwoda, M., et al., 2021. Sponges as bioindicators for microparticulate pollutants? *Environmental Pollution*. 268(A), 115851. DOI: <https://doi.org/10.1016/j.envpol.2020.115851>
- [28] Pansini, M., Azzini, F., Bavestrello, G., et al., 2004. Notes on the sponge fauna of Vietnam and preliminary data on the Ha Long Bay April 2003 survey. In: Thung, D.C., Sarti, M. (Eds.). *Conservation of Biodiversity in Vietnam's Coastal Zone*. Vietnam National University Publishing House: Hanoi, Vietnam. pp. 194–203.
- [29] Hooper, J.N.A., Kennedy, J.A., 2000. Annotated checklist of sponges (Porifera) of the South China Sea region. *The Raffles Bulletin of Zoology*. 8, 125–207.
- [30] Thuoc, C.V., 2015. Data on the species composition and the distribution of harmful marine epiphytic microalgae living on coral reefs in the North Vietnam. *Academia Journal of Biology*. 24(2), 22–30.
- [31] Yet, H.H., Lang, V.K., 1996. Data on species composition and distribution of hard corals (Scleractinia) in Ha Long Bay. *Journal of Biology*. 18(1), 7–13.
- [32] Patrício, J., Elliott, M., Mazik, K., et al., 2016. DP-SIR—Two decades of trying to develop a unifying framework for marine environmental management? *Frontiers in Marine Science*. 3, 177. DOI: <https://doi.org/10.3389/fmars.2016.00177>
- [33] Andruliewicz, E., 2005. Developing the DPSIR framework of indicators for management of human

- impact on marine ecosystems, Baltic Sea example. In: Gonenc, I.E., Koutitonsky, V.G., Rashleigh, B., et al. (Eds.). *Assessment of the Fate and Effects of Toxic Agents on Water Resources*. Springer: Dordrecht, The Netherlands. pp. 225–243. DOI: [https://doi.org/10.1007/978-1-4020-5528-7\\_10](https://doi.org/10.1007/978-1-4020-5528-7_10)
- [34] European Commission, 2008. *Marine environment: EU policies to protect Europe’s oceans, seas and coasts*. Available from: [https://environment.ec.europa.eu/topics/marine-environment\\_en](https://environment.ec.europa.eu/topics/marine-environment_en) (cited 29 September 2025).
- [35] Douvere, F., 2015. *World Heritage Marine Sites—Managing Effectively the World’s Most Iconic Marine Protected Areas: A Best Practice Guide*. United Nations Educational, Scientific and Cultural Organization: Paris, France.