Assessing Coastal Industrial Pollution and Climate Change Impacts Through Integrated Modeling for Sustainable Management in Hai Phong, Vietnam

Pham Thi Song Thu[1], Doan Quang Tri[2]† iD **and Nguyen Van Hong[3]**

[1]President Ho Chi Minh's Vestige in the Presidential Palace Area, Ha Noi, Vietnam

[2]Hydrometeorology Information and Data Center, Viet Nam Meteorological and Hydrological Administration, Ha Noi, Vietnam

[3]Sub-Institute of Hydro-Meteorology and Climate Change, Ho Chi Minh City, Vietnam

†Corresponding author: Doan Quang Tri; doanquangtrikttv@gmail.com

ABSTRACT

The rapid development of industries, agriculture, and urbanization has led to an increase in the amount of pollutants released into the soil, water, and air, affecting ecosystems and public health. This study assesses the impacts of environmental pollution in the coastal areas of Hai Phong, Vietnam, under the influence of climate change and proposes adaptation solutions to ensure sustainable development. The research utilizes the MIKE 21 modeling system (SW, FM, Ecolab) to simulate wave propagation, hydrodynamics, and the dispersion of pollutants (DO, BOD_5, COD, TSS, Fe, and Coliform) in the study area's ecosystem. The key results of the study are (1) Calibration and validation of wave, hydrodynamic, and water quality models to determine appropriate parameter sets; (2) Assessing the impact of pollutants from major coastal industrial zones in Hai Phong under climate change scenarios; (3) Developing an environmental pollution risk zoning map to identify high-risk areas and propose adaptation solutions to ensure the sustainable development of the study area's ecosystem. Our findings provide crucial information for effectively managing coastal ecosystem pollution, mitigating the impacts of climate change, and promoting sustainable development in Hai Phong's coastal region.

INTRODUCTION

Coastal water pollution caused by industrial activities has been widely studied worldwide, particularly in rapidly developing regions. Numerous studies highlight that wastewater discharge from industrial zones contributes significantly to the degradation of coastal ecosystems by increasing levels of organic pollutants, heavy metals, and microbial contaminants (Oladimeji et al. 2024, Jin et al. 2025, El-Sharkawy et al. 2025, Hidayati et al. 2025). Industrial effluents containing high concentrations of biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), and total suspended solids (TSS) have been shown to reduce dissolved oxygen (DO) levels, leading to eutrophication and biodiversity loss (Maddah 2022).

Studies in China and India emphasize the impact of industrial discharges on marine biodiversity and water quality (Dai et al. 2023, Sun et al. 2024, Wang et al. 2024). Zhang et al. (2025) conducted a study in the Yangtze River Delta, revealing that the location, population density, site area, average annual precipitation, land-use characteristics, wastewater discharge, environmental protection expenditure, and wastewater treatment costs influence aquatic ecosystems. Similarly, Sharma et al. (2021) examined coastal industrial pollution in Mumbai and reported that untreated effluents caused long-term ecological damage to mangroves and fisheries. These findings highlight the need for integrating hydrodynamic modeling approaches to

assess pollutant dispersion in coastal waters under various environmental conditions.

Coastal areas play a crucial role in economic development, supporting industries, fisheries, tourism, and urban settlements (Hai & Vinh 2021, Pascoe et al. 2023, Chang et al. 2024, Wang et al. 2024, Wang et al. 2025). However, rapid industrialization, agricultural expansion, and urbanization have significantly contributed to environmental degradation, particularly in developing coastal cities (Tri et al. 2019). The discharge of untreated or partially treated wastewater, industrial effluents, and agricultural runoff has led to increased levels of organic matter, heavy metals, and microbial contamination in coastal waters, affecting biodiversity and ecosystem services (Tran et al. 2018, Le et al. 2022, Singh et al. 2023, Gomes 2024, Taher et al. 2024). Vietnam's coastal regions are increasingly affected by industrial pollution due to rapid economic development and urbanization. Studies have reported high levels of pollutants, such as COD, BOD_5, TSS, and heavy metals, in major industrial hubs like Hai Phong, Da Nang, and Ho Chi Minh City (Phuong 2014, Tri et al. 2019, Tong et al. 2024, Tinh & Quoc 2025). Research in the coastal areas of the Mekong Delta has demonstrated that industrial discharges significantly contribute to eutrophication and marine biodiversity loss (Anh et al. 2010, Trinh 2017, Whitehead et al. 2019, Nguyen et al. 2024).

Despite existing environmental regulations, many industrial zones still discharge untreated or partially treated wastewater into coastal waters, exacerbating pollution issues. Hai et al. (2021, 2025) used hydrodynamic models to analyze the dispersion of pollutants in the coastal waters of Thanh Hoa and the Cat Ba - Ha Long coastal area emphasized the role of climate change in altering pollutant transport mechanisms. These studies underscore the necessity of integrating climate change scenarios into water pollution assessments to develop adaptive strategies.

Hai Phong is one of Vietnam's most important industrial and port cities, playing a crucial role in the country's economic development. However, its rapid industrialization and port activities have led to increasing environmental challenges, particularly in coastal water pollution. Major industrial zones, such as Dinh Vu-Cat Hai and Nam Cau Kien, discharge significant amounts of pollutants into surrounding water bodies, negatively impacting marine ecosystems (Tri et al. 2019, Vinh et al. 2020, Nam et al. 2025, Hai et al. 2025). Monitoring data indicate that wastewater from these industrial clusters contains high concentrations of pollutants, including biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), iron (Fe), and coliform bacteria, often exceeding permissible limits in several locations (Duong & Le 2019, Duong et al. 2020, Hai et al. 2025, Le et al. 2023a, 2023b). The accumulation of these pollutants not only degrades water quality but also threatens marine biodiversity and public health. Despite the implementation of various environmental management policies, pollution levels in Hai Phong's coastal waters remain alarmingly high. This situation underscores the urgent need for a comprehensive scientific assessment to evaluate pollutant dispersion patterns and develop effective mitigation strategies for sustainable coastal management.

Studies using hydrodynamic models, such as MIKE 21, have provided insights into pollutant dispersion in Hai Phong's coastal waters. Previous studies have employed numerical modeling to simulate the transport of heavy metals and organic pollutants, demonstrating the spatial extent of pollution plumes (Tri et al. 2019, Thu & Tri 2023, Thu et al. 2023). However, limited research has incorporated climate change scenarios into pollution assessments, highlighting a critical gap in existing studies.

To address this gap, our study applies the MIKE 21 modeling system to evaluate pollutant dispersion under different climate change scenarios, and to develop an environmental pollution risk zoning map for the region. This approach provides a comprehensive assessment of the interaction between industrial discharges, hydrodynamic processes, and climate change, contributing to sustainable coastal management in Hai Phong.

Climate change further exacerbates these environmental challenges. Rising sea levels, increasing temperatures, and extreme weather events alter hydrodynamic conditions and pollutant dispersion patterns, making it more difficult to predict and control pollution hotspots (IPCC 2021). Changes in rainfall intensity and frequency affect pollutant runoff from land-based sources, intensifying coastal water pollution. Understanding how pollution interacts with climate change is crucial for designing adaptive management strategies to enhance coastal resilience.

While previous studies have investigated industrial pollution in Hai Phong (Tri et al. 2019, Vinh et al. 2020, Thu & Tri 2023, Hai et al. 2025), limited research has integrated hydrodynamic modeling with climate change scenarios to evaluate long-term environmental impacts. This study addresses this gap by employing the MIKE 21 modeling system to simulate wave propagation, hydrodynamic processes, and pollutant dispersion under projected climate conditions. By generating an environmental pollution risk zoning map, our research provides a novel framework for identifying high-risk areas and developing adaptive solutions tailored to future climate scenarios. The findings contribute to ongoing efforts in sustainable

coastal management and inform climate adaptation policies in Vietnam.

It can be observed that in Vietnam, in general, and in the study area in particular, numerous projects and research studies have been conducted to assess the impacts of climate change on coastal areas; evaluate coastal water quality; and examine the adaptive capacity for socio-economic development in coastal regions. However, no study to date has comprehensively integrated all aspects from assessing the current status of marine pollution to simulating and evaluating the dispersion of pollutants from coastal economic activities and the quality of receiving marine waters under the influence of climate change, to propose comprehensive and effective adaptation solutions.

This study's objectives are as follows: (1) To assess the impact of pollutant dispersion under climate change scenarios on six key parameters: dissolved oxygen (DO), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), iron (Fe), and coliform bacteria in the coastal waters of Hai Phong; (2) To develop an environmental pollution risk zoning map to identify high-risk areas, supporting environmental management and spatial planning; (3) To propose adaptive solutions and sustainable management strategies to mitigate the impacts of industrial pollution and climate change on Hai Phong's coastal environment.

MATERIALS AND METHODS

Description of Study Site

The coastal waters of Quang Ninh - Hai Phong exhibit high marine biodiversity, reflected in the diversity of ecosystems and species composition of the marine biota. Typical marine ecosystems in this region include mangrove forests, coral reefs, seagrass beds, estuaries (including lagoons and bays), tidal flats, and coastal karst lakes. Additionally, the diverse coastal habitats contribute to structural diversity within each ecosystem. These ecosystems serve as habitats for a wide variety of species and abundant fishery resources. Some ecosystems also provide important ecological services, such as coastal protection and erosion prevention (mangrove forests, coral reefs, seagrass beds); breeding and nursery grounds for aquatic species (mangrove forests, coral reefs, seagrass beds, estuaries); and scenic landscapes for marine tourism, especially diving (coral reefs) (MoNRE 2013).

The low tidal flats are mainly distributed inside Cua Luc Bay (in the northern part of the bay), the western areas of the bay around the islands of Tuan Chau and Hoang Tan extending to Phu Long, and the estuarine region of the Bach Dang River. Although the species composition of soft-bottom intertidal communities in these areas is less diverse than that of offshore islands, they form important and highly productive fishing grounds with significant harvest yields. These include blood cockles and hairy cockles (Tuan Chau), clams and ark clams (from Cua Luc to Cat Hai), marine worms and sandworms (from Tuan Chau to Phu Long), and estuarine oysters (Chanh River - Yen Hung) (MoNRE 2013). In the Hai Phong - Quang Ninh marine area, six species of seagrasses have been identified, primarily distributed in the Nha Mac lagoon, which accounts for 3% of Vietnam's total seagrass meadow area.

Coral reefs are a characteristic ecosystem of the coastal waters in the study area, possessing high economic and biodiversity value. They are widely distributed around islands on the continental shelf, including the Co To Archipelago, Ha Long-Cat Ba area, and Bach Long Vi. These regions hold significant potential for biodiversity conservation, natural marine seed resources, marine biological productivity, and ecotourism. Key areas where coral reefs are well-developed include the southeastern part of the Cat Ba Archipelago, Ha Long Bay extending to Cong Do Island near Bai Tu Long Bay, and the outer islands of Bai Tu Long Bay, such as the Co To Archipelago and Tran Island. The coral reef ecosystem in this region has high biological productivity and supports a high level of biodiversity. The ecosystem map of the study area is shown in Fig. 1.

Data Collection

The data used in this study include: (1) Digital Elevation Model (DEM) of the Hai Phong coastal area (used for grid calculations, data obtained in 2010); (2) Base map of Hai Phong City (used for editing map layers, data from 2020); (3) Water level data from Hon Dau station in 2020 for model calibration and in 2021 for validation of the MIKE 21 FM hydrodynamic model; (4) Measured wave and wind data from Hon Dau station in 2020 and 2021, used for calibration and validation of the wave model; (5) Discharge reports from industrial zones within the study area, including Dinh Vu Industrial Park, Shinetsu Company, Dinh Vu Port, and Tan Vu Port, to obtain information on pollution sources and discharge volumes (collected from the 2021 statistical reports of industrial zones in Hai Phong City); (6) Water quality parameter data from environmental monitoring stations within the study area, used for calibration and validation of the water quality model (collected from the environmental status reports of Hai Phong Province in 2015 and 2016); (7) Time series of observed water quality data in the coastal waters of Hai Phong City (collected in 2015 and 2016); (8) Socio-economic development plan of Hai Phong City for the period 2030-2050; (9) Statistical yearbooks of Hai Phong
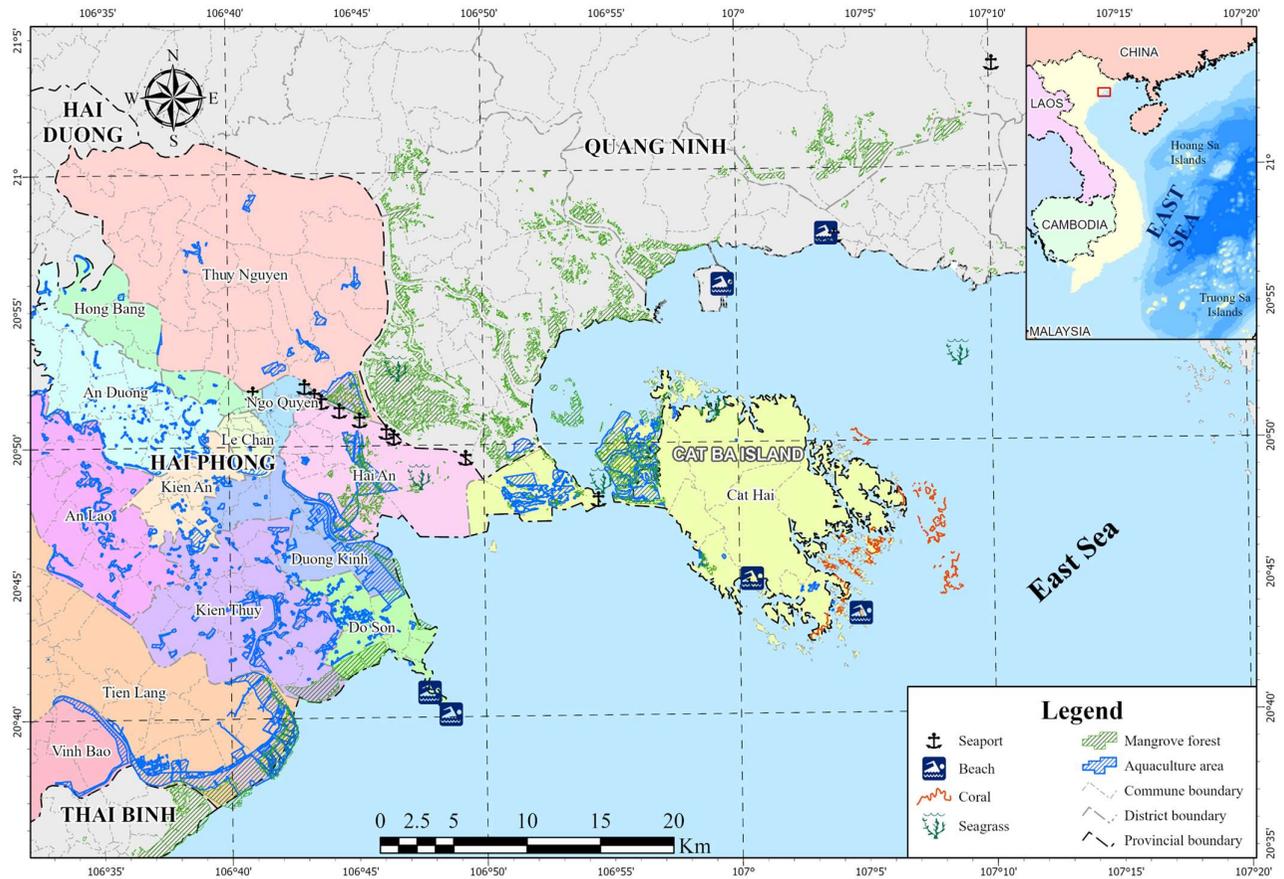
Fig. 1: Ecosystem map of the study area.

City for 2022 and 2023; (10) Documents on aquaculture and coastal ecosystems in Hai Phong City (inherited from research project (Khac 2020)); (11) Climate change scenarios published in 2020 (MoNRE 2020).

Methodology

The study approach is described in the research framework diagram in Fig. 2.

Description of Models

a) *MIKE 21 Spectral-wind Wave Model:* Wave field data are crucial for sediment transport and pollutant dispersion calculations. In this project, MIKE 21 SW is used to simulate the wave field for the study area (DHI 2014a). MIKE 21 SW is a spectral wave model that operates on an unstructured mesh. This model calculates the generation, dissipation, and propagation of waves induced by wind and swell in offshore and coastal regions. The dynamics of gravity waves are simulated based on the wave action density equation. When applied to small regions, the fundamental

equations are used in a Cartesian coordinate system, whereas for large areas, a spherical coordinate system is applied. The wave action density spectrum varies spatially and temporally as a function of two wave phase parameters. The fundamental equations are formulated in both Cartesian coordinates for small-scale applications and spherical coordinates for larger-scale applications. MIKE 21 SW incorporates the following physical phenomena: Wave growth due to wind forcing; Nonlinear wave-wave interactions; Wave dissipation due to whitecapping; Wave dissipation due to bottom friction; Wave dissipation due to wave breaking; Refraction and shallow water effects due to depth variations; Wave-current interactions; Influence of time-dependent depth changes (DHI 2014a).

b) *MIKE 21 FM Hydraulic Model:* The flow module is developed based on the finite element mesh method. It is derived from the numerical solution of the Navier-Stokes equations for incompressible fluids in two or three dimensions, combined with the Boussinesq approximation and the hydrostatic pressure assumption
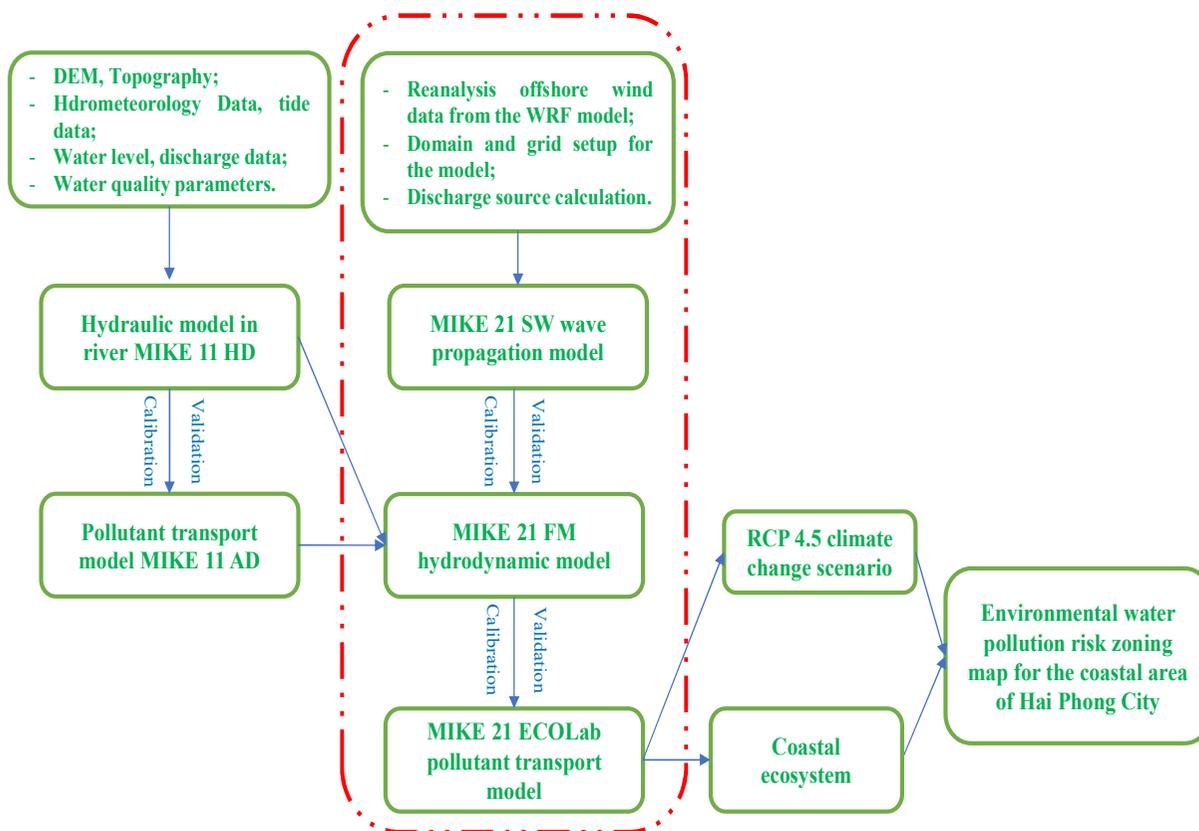
Fig. 2: The study framework flowchart.

(DHI 2014b-e). As a result, the module includes the following equations: continuity equation, momentum equation, temperature equation, salinity equation, and density equation, with closure achieved through a turbulence closure scheme. In the three-dimensional case, a sigma coordinate system is used. The spatial discretization of the fundamental equations is performed using the central finite volume method. The spatial domain is discretized by dividing the continuous domain into non-overlapping grid cells/elements. In the horizontal direction, an unstructured mesh is used, while in the vertical direction (for three-dimensional cases), a structured mesh is applied. In the two-dimensional case, elements can be triangular or quadrilateral. In the three-dimensional case, elements can be triangular or quadrilateral prisms, with surface elements taking the form of triangles or quadrilaterals.

c) *MIKE 21 EcoLab Water Quality Model:* The EcoLab model is integrated within MIKE 21, built on the HD hydraulic module, which calculates water levels and two-dimensional unsteady flows in a vertically homogeneous fluid layer (DHI 2014f-i). The mass and momentum conservation equations are vertically integrated to describe the variations in water levels and flow dynamics. The computational results from the hydraulic module enable the simulation of hydrodynamic physical processes, forming the basis and input for calculations in EcoLab. When combined with the advection-diffusion module, the equations are formulated for non-conservative substances. The numerical equations in EcoLab are solved using a time-dependent integration approach, incorporating both biochemical processes within EcoLab and transport-diffusion processes.

Establishing Models for the Study Area

a) *MIKE 21 SW Model:* The computational domain for this study is the coastal area of Hai Phong City, with coordinates ranging from 20°01'N to 21°31'N and 106°38'E to 107°14'E. The computational grid is constructed using a combination of unstructured and square grids, with a total of 10,512 grid cells and 7,047 grid nodes; the study area is simulated using an unstructured grid. Input data for the model boundary conditions include wave data, wind data, and water
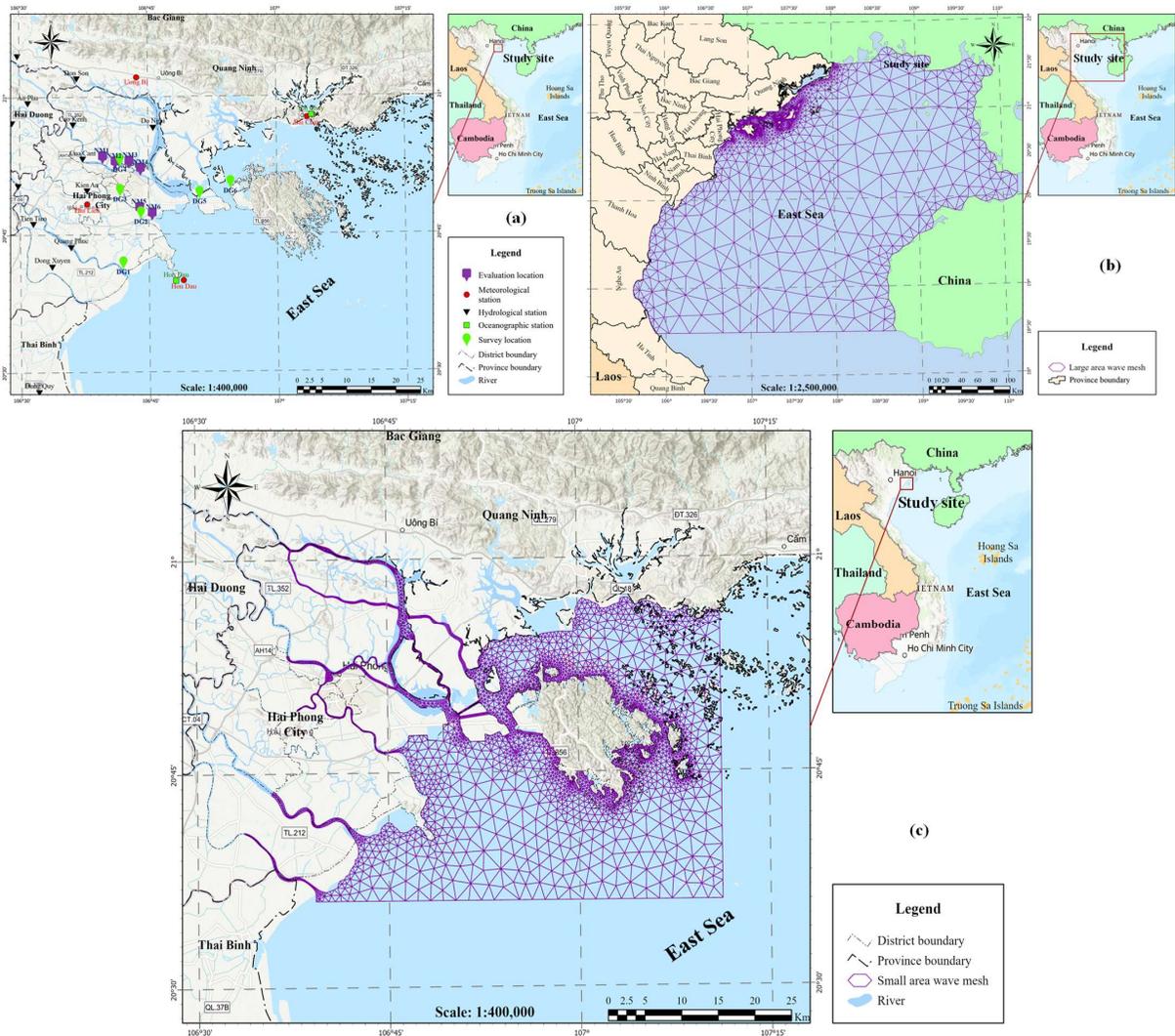
Fig. 3: (a) Meteorological, hydrological and ocenographical stations; (b) Establised mesh of tidal prediction; (c) Established mesh of wave propagation, hydraulic and water quality (Thu & Tri 2023).

levels collected from hydrographic stations within the study area. To simulate waves in the Hai Phong coastal region, the study first models waves for the larger surrounding sea area (large-scale waves) before transferring them to the shallow water coastal area of Hai Phong (small-scale waves). Fig. 3 presents the computational grids for the large-scale wave model and the study area wave model. The setup and configuration of the wave propagation domain for the study area were based on previous research findings (Thu & Tri 2023).

b) *Setup and Calibration of the MIKE 21 HD Hydraulic Model:* Input data used to set up and calibrate model in this study includes:

Study Area Topography: Obtained from nautical charts provided by the Vietnam People's Navy and survey data from previous projects.

River Discharge at River Mouths: Inherited from the calibrated and validated MIKE 11 model of the Red River - Thai Binh River system in the study by Dao (2023).

Offshore Boundary Water Levels: Computed using the tidal propagation tool in the MIKE 21 model.

Wind Data: Collected from the Hon Dau meteorological station.

Water Levels for Calibration and Validation: Measured at the Hon Dau Hydrographic Station.

Discharge from Industrial Zones: Includes wastewater discharge from factories, industrial zones, and industrial clusters within the study area.

Table 1: Information on some sources of waste from industrial parks/industrial clusters.

No	Wastewater discharge sources	Discharge (m^3/s)
1	Dinh Vu Industrial Zone	0.11
2	Tan Vu Industrial Zone	0.02
3	Hai Phong Cement Plant	0.13
4	Bach Dang Shipyard	0.02

Marine Boundaries: Water levels at the eastern and southern boundaries of the computational domain, calculated using the tidal propagation tool in MIKE 21 based on tidal harmonic constants derived from observed data at the Hon Dau Hydrographic Station.

River Boundaries: Discharge at various river locations simulated using the MIKE 11 model for the entire Red River - Thai Binh River system, including the Da Bac River, Cam River, Lach Tray River, and Van Uc River.

The model was developed using an unstructured computational grid, with a total of 9,083 cells and 4,857 grid nodes in the computational domain, simulating the dry season period with a time step of 60 seconds.

c) *Setup and Calibration of the MIKE 21 EcoLab Pollutant Transport Model:* This study establishes a simulation model to assess water quality from several coastal industrial zones in Hai Phong City, focusing on six pollution parameters: Total suspended solids (TSS), Coliform, Biochemical Oxygen Demand (BOD$_5$), Dissolved Oxygen (DO), Chemical Oxygen Demand (COD), and heavy metal Fe. The Hai Phong coastal area hosts numerous large industrial parks and clusters. The study collected and compiled data on major industrial zones in the area and represented them as point sources in the model. While this study did not gather complete data on all wastewater sources from residential areas and small industrial zones discharging into the river system, it incorporated measured river water quality data during calibration and validation. This ensures a relatively accurate representation of water quality in the Hai Phong coastal and estuarine river system. Table 1 presents information on major wastewater discharge sources in the study area.

d) *Climate Change Scenarios and Analysis of Simulation Results:* To assess marine water pollution under the impact of future economic development activities on coastal aquaculture in Hai Phong, the study, after finding the appropriate set of model parameters, established an input data set corresponding to changes in rainfall and tidal water levels based on the climate change and sea level rise scenarios for Vietnam published by the Ministry of Natural Resources and Environment in 2020 (MoNRE 2020). The study selects the RCP4.5 scenario - a low-moderate greenhouse gas concentration scenario to simulate and calculate the potential impact of environmental pollution parameters on the coastal area of the study region. This is because it is a scenario with stable radiation forcing, where the total radiation forcing reaches approximately 4.5 W/m² by 2065 and remains stable until 2100, without any sudden increase over a long period (Tables 2 and 3).

The temperature and rainfall data were updated in the intermediate calculation step to determine the corresponding changes in river discharge based on the variation in rainfall, which were then used to update the boundary conditions of the MIKE 21 model.

Similarly, water level data under the climate change scenario were processed to generate tidal boundary conditions according to the scenario, which were then input into the MIKE 21 model.

With the above analysis, the study focuses on simulating and developing a zoning map of environmental conditions related to coastal aquaculture in the study area in the context of climate change under the scenario: Evaluation of marine water environment using rainfall, temperature, and sea level data according to the 2020 Climate Change Scenario RCP 4.5 for the period 2046-2065, with updated discharge sources based on expected future emissions according to the socio-economic development plan of Hai Phong City for the years 2030-2050.

Table 2: Changes in average temperature and rainfall in spring under the RCP 4.5 scenario (MoNRE 2020).

Temperature (^{o}C)		Precipitation (%)	
2046-2065	2080-2099	2046-2065	2080-2099
1.6 (1.0 ÷ 2.2)	2.1 (1.3 ÷ 3.0)	17.3 (3.2 ÷ 29.8)	32.3 (11.7 ÷ 51.2)

Table 3: Sea level rise according to the RCP 4.5 scenario (Unit: cm) (MoNRE 2020)

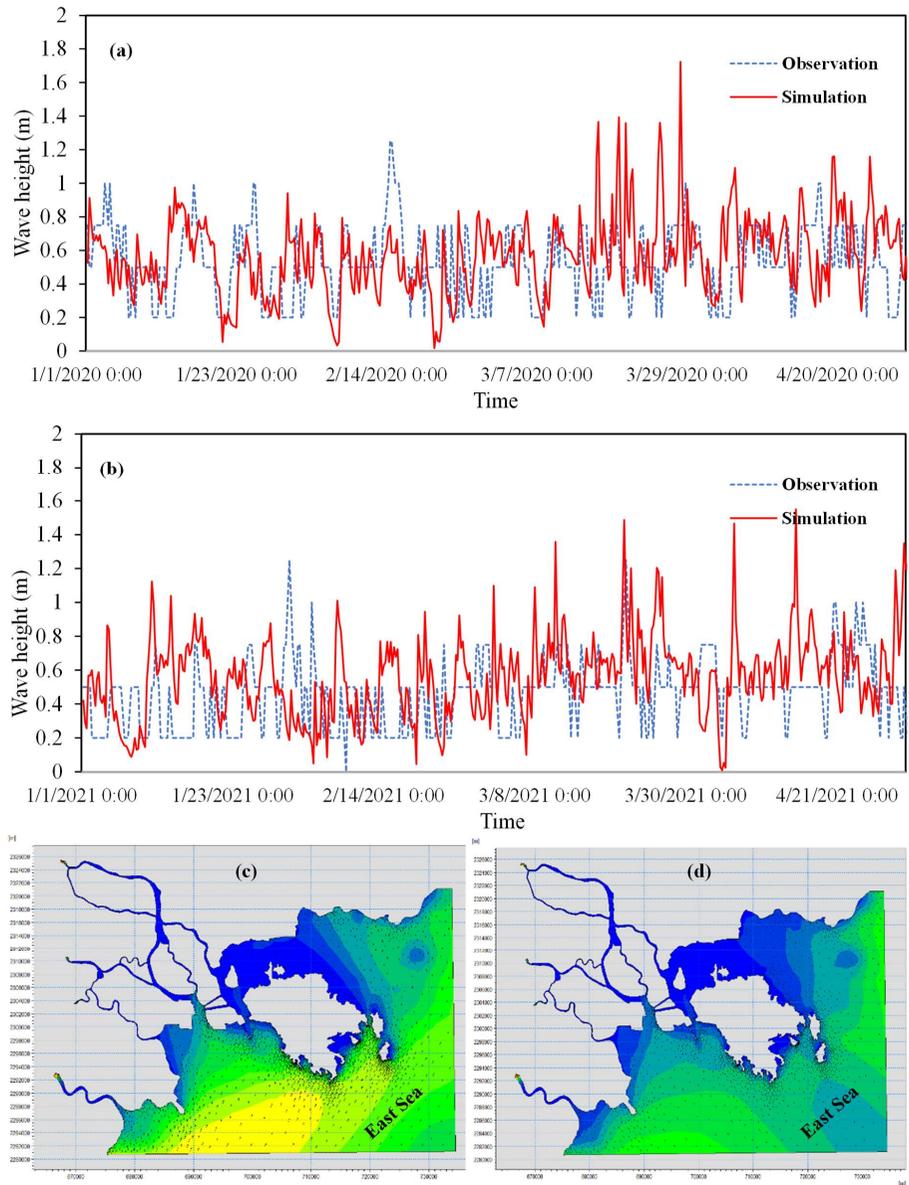| Region	Time milestones of the 21st century							
	2030	2040	2050	2060	2070	2080	2090	2100
Mong Cai - Hon Dau	12 (7÷17)	17 (10÷23)	22 (14÷30)	28 (17÷39)	34 (21÷47)	40 (25÷57)	46 (29÷66)	52 (33÷75)

Fig. 4: Calibration and validation of the wave model: (a) Mean wave height in 2020; (b) Mean wave height in 2021; Wave simulation results for the study area: (c) 2020; (d) 2021 (Thu & Tri 2023).

RESULTS

Results of the MIKE 21 SW, MIKE 21 FM, and MIKE 21 EcoLab Models

a) *Calibration and Validation Results of the MIKE 21 SW Wave Model:* The wave model was developed for the study area, with simulation results calibrated using observed data from the Hon Dau station in 2020 and validated in 2021, focusing on the mean wave height parameter. The calibration and validation results of the wave model are shown in Figs. 4a-4b.

The calibration results for mean wave height in 2020 and 2021 indicate that the MIKE 21 SW wave model effectively simulates mean wave height. The calibrated and validated MIKE 21 SW model parameters are presented in Table 4. Key values include wave propagation directions, bottom friction, and whitecapping parameters (Cdis = 4.5 and Delta = 0.5), while depth-induced wave breaking is set at 0.73. The initial conditions are defined as deep-water spectra using the JONSWAP spectrum.

Boundary conditions include two open boundaries, allowing wave energy exchange between the interior and

exterior of the computational domain. After constructing the deep-water wave model for the study area, wave transmission from the large-scale wave model to the study region was performed. The simulation results for waves in the study area for 2020 and 2021 are shown in Figs. 4c-4d (Thu & Tri 2023).

b) *Calibration and Validation Results of the MIKE 21 FM Hydraulic Model:* The calibration and validation of the MIKE 21 FM hydraulic model for the study area were conducted for the periods from January to March 2020 for model calibration and from January to March 2021 for model validation. The results are presented in Figs. 5a-5b.

The accuracy of the calibration and validation process was evaluated using the Nash Sutcliffe efficiency coefficient and the correlation coefficient between the computed results and observed data at the Hon Dau station. The calibration and validation results indicate that the MIKE 21 FM model can simulate the hydrodynamics relatively accurately, with indices ranging from 0.85 to 0.90, are considered acceptable to good. The model captures the tidal regime in the area relatively well; however, it does not fully capture the tidal troughs and peaks accurately, with an error margin of approximately 0.1 m.

The optimal parameter set for the MIKE 21 FM model identified the following values: turbulent viscosity coefficient (0.28), Manning's roughness coefficient (57 m$^{1/3}$/s), wind friction coefficient (0.002), and computational time step (60 seconds). These values ensure reliability and can be applied to simulate water quality for the study area. With these results, the model is deemed reliable for simulating and assessing pollutant dispersion process from industrial discharge sources into the study area (Thu & Tri 2023).

c) *Calibration and Validation Results of the MIKE 21 EcoLab Water Quality Model:* The study collected pollutant parameter data at discharge sources and several locations within the study area, combined with water quality measurement data from 2015 and 2016. The calibration and validation results of the water quality model at various locations in the study area are shown in Table 4.

The calibration and validation processes were conducted for six key parameters: DO, BOD$_5$, COD, TSS, Fe, and Coliform at six monitoring and sampling locations (NM1-NM6). The 2015 calibration results indicate that the error between simulated and observed concentrations ranged from 5% to 19%. This suggests that the water quality
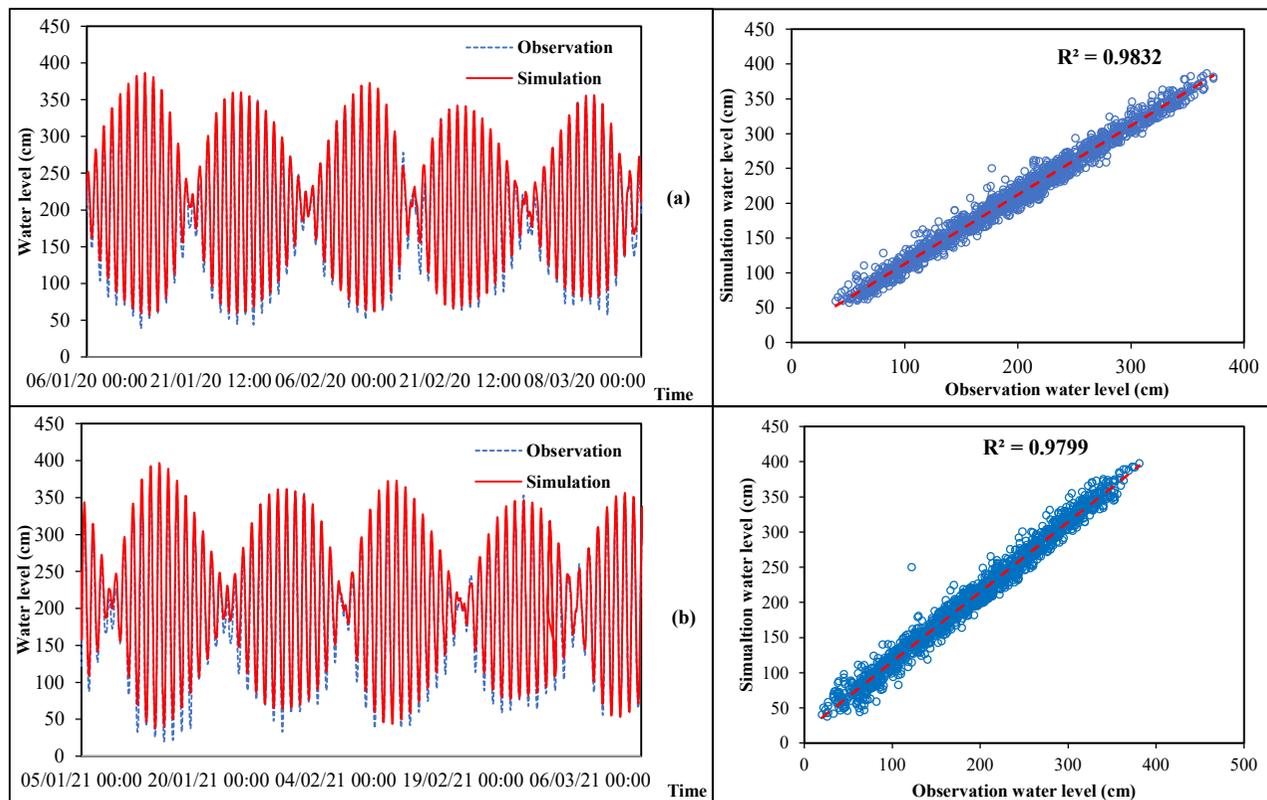

Fig. 5: The calibration (a) and validation (b) results of water level at Hon Dau station (Thu & Tri 2023).

Table 4: Evaluation of Calibration and Validation Errors of the Water Quality Model (Thu & Tri 2023).

No	Calibration (2015)						Validation (2016)					
	Coliform	BOD_5	COD	TSS	Fe	DO	Coliform	BOD_5	COD	TSS	Fe	DO
NM1	-10%	-8%	-10%	-8%	-18%		-8%	-13%	-17%	6%	-19%	
NM2	-8%	-10%	8%	12%	-22%		-7%	-7%	-19%	9%	-21%	
NM3	-5%	-5%	-11%	-16%	12%		-7%	-9%	-15%	-24%	-13%	-16%
NM4	-9%	-8%	-15%	-15%	14%		-7%	-7%	-14%	-21%	-11%	-15%
NM5	-7%	14%	-11%	-19%		-8%	-10%	-11%	9%	-19%		15%
NM6	-11%	12%	-12%	13%		-14%	-15%	-10%	6%	13%		8%

Table 5: Parameters of MIKE 21 model.

No	Parameters	Selection value
1	Turbulent viscosity coefficient - Smagorinsky	0.28 (m^2/s)
2	Bottom friction coefficient - Manning's coefficient	57 ($m^{1/3}$/s)
3	Wind friction coefficient	0.0027
4	Time step	60 (s)
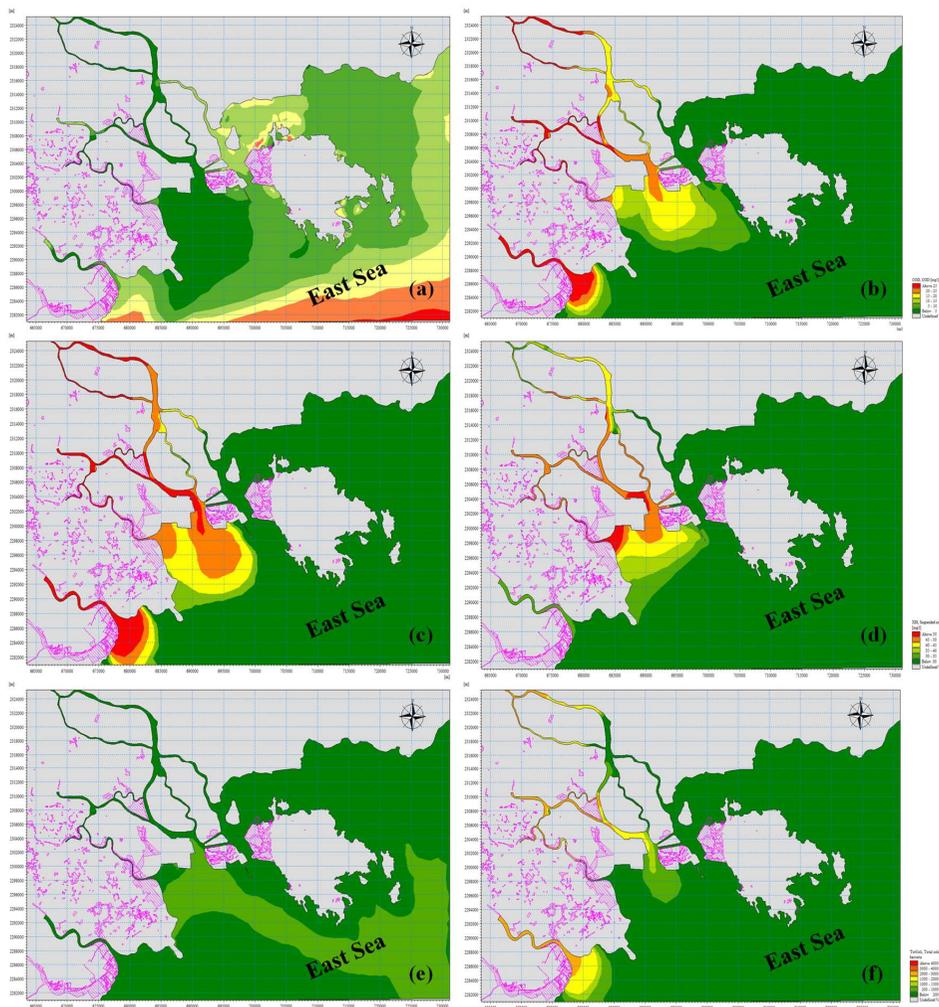
Fig. 6: Results of climate change scenario simulations: (a) DO; (b) COD; (c) BOD_5; (d) TSS; (e) Fe; (f) Coliform (Thu et al. 2023).

model parameters are relatively well-suited for the study area. However, to ensure a more accurate and objective assessment, the model was validated for 2016 using the same set of water quality parameters (Thu & Tri 2023).

The validation results of the water quality model for 2016 show that the error between the simulated and observed pollutant concentrations ranged from 6% to 24%. This indicates that the water quality model parameters are relatively well-suited for the study area. The model parameters mentioned in Table 5, were used to simulate the climate change scenarios established above.

Simulation Results of Marine Pollution Scenarios Considering Climate Change

Based on the selected climate change scenarios, the study utilized MIKE 21 Ecolab to simulate the dispersion of DO, BOD_5, COD, TSS, Fe, and Coliform in the study area. The simulation results indicate a decreasing trend in DO concentration, while the concentrations of BOD_5, COD, TSS, Fe, and coliform show an increasing trend. The scenario was simulated with input boundaries including

wastewater discharge sources from industrial parks (KCN) and industrial clusters (CCN) planned for future development (with significant increases expected), along with rising sea levels and changing rainfall patterns according to the climate change scenario. Figs. 6a-6f illustrate the variations in the dispersion of key pollution parameters in the coastal waters of Hai Phong City.

Assessment of Pollutant Impacts on the Coastal Ecosystem

a) *Evaluation of DO Concentration Effects on the Ecosystem:* Any change in DO (dissolved oxygen) levels in water can significantly impact the normal development of aquatic organisms. When DO concentrations become too low, aquatic species experience difficulty in respiration, reduced activity, and overall adverse effects on the ecosystem. DO not only serves as an essential oxygen source for farmed aquatic organisms but also promotes the growth of aerobic microorganisms, enhances the decomposition of organic matter, and helps mitigate harmful substances. Maintaining appropriate
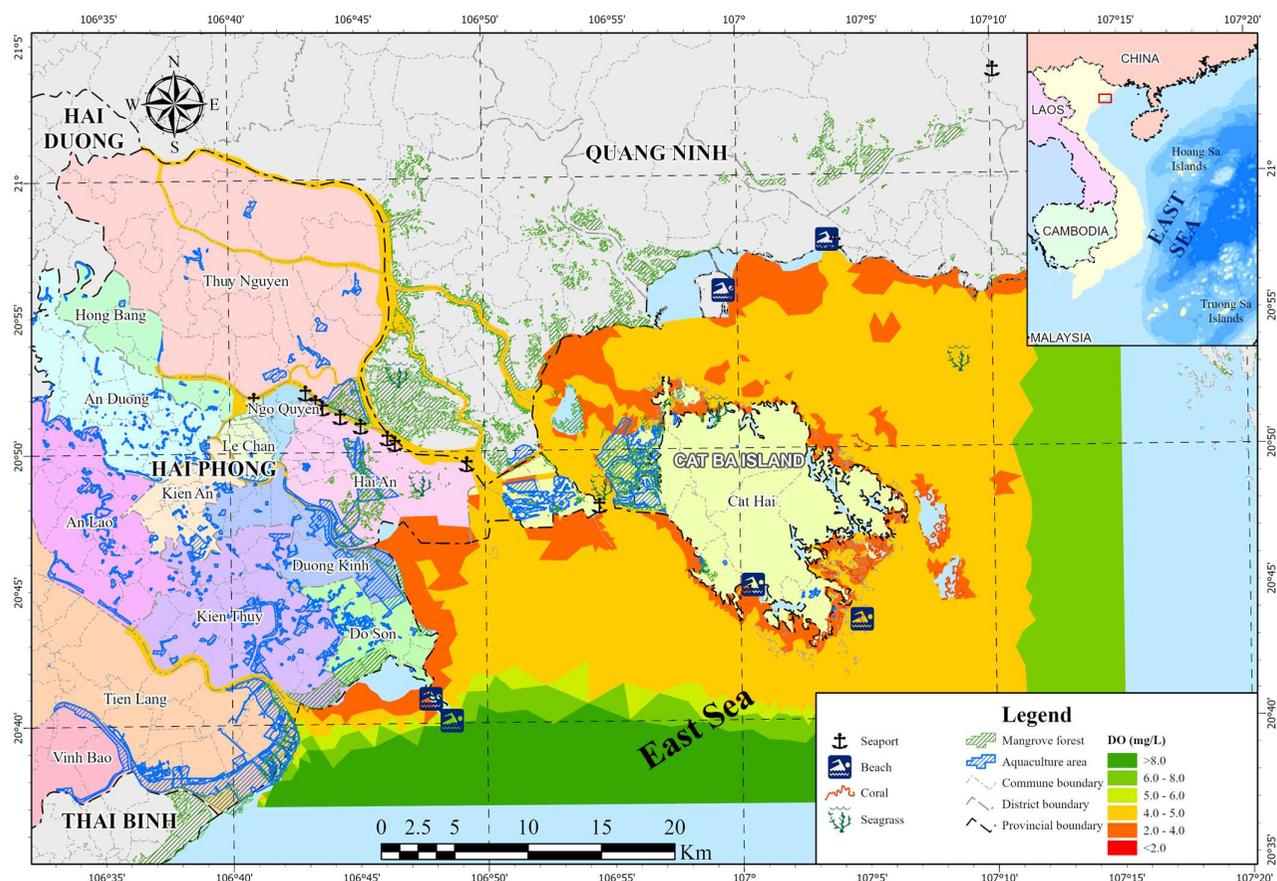

Fig. 7: The impact level of DO on the ecosystem in the study area.

DO levels also inhibits anaerobic microorganisms and boosts the immune systems of aquatic species.

The simulation results of DO dispersion in the coastal waters of the study area indicate reduced DO concentrations, which negatively affect the Hai Phong coastal ecosystem, including seagrass beds and various aquatic species in the region (Fig. 7).

b) *Assessment of the impact of COD concentration on the ecosystem:* When COD increases, the decomposition of organic matter in wastewater consumes a large amount of dissolved oxygen. This causes a significant decrease in oxygen levels in the water, leading to suffocation and mass death of aquatic species. The underwater ecosystem is disrupted, affecting the food chain and biodiversity.

The simulation results of COD dispersion from industrial and coastal wastewater sources in Hai Phong show that the COD concentration in the coastal area remains relatively low, and generally within the permissible limits for water used in agriculture and maritime traffic. However, the concentration is higher in river sections near the estuaries, impacting the mangrove ecosystem along the river, particularly in the Nha Mac lagoon area, where the seagrass ecosystem is concentrated and where the COD concentration is notably high (Fig. 8).

c) *Assessment of the impact of BOD_5 concentration on the ecosystem:* The BOD_5 concentration follows the same trend as the COD concentration in the study area. High BOD_5 indicates the presence of significant amounts of organic matter in the wastewater, which requires oxygen for decomposition. If BOD_5 is high, the wastewater will consume more oxygen, leading to a decrease in oxygen levels in the water environment and negatively affecting aquatic organisms.

As shown in Fig. 9, BOD_5 concentrations are at alarming levels in the Bach Dang River, Cam River, and Van Uc River areas. Among them, the lower reaches of the Bach Dang River, which have relatively rich seagrass and mangrove ecosystems, are particularly vulnerable to the elevated BOD_5 concentrations.

d) *Assessment of the impact of TSS concentration on the ecosystem:* TSS affects water clarity, so the higher the
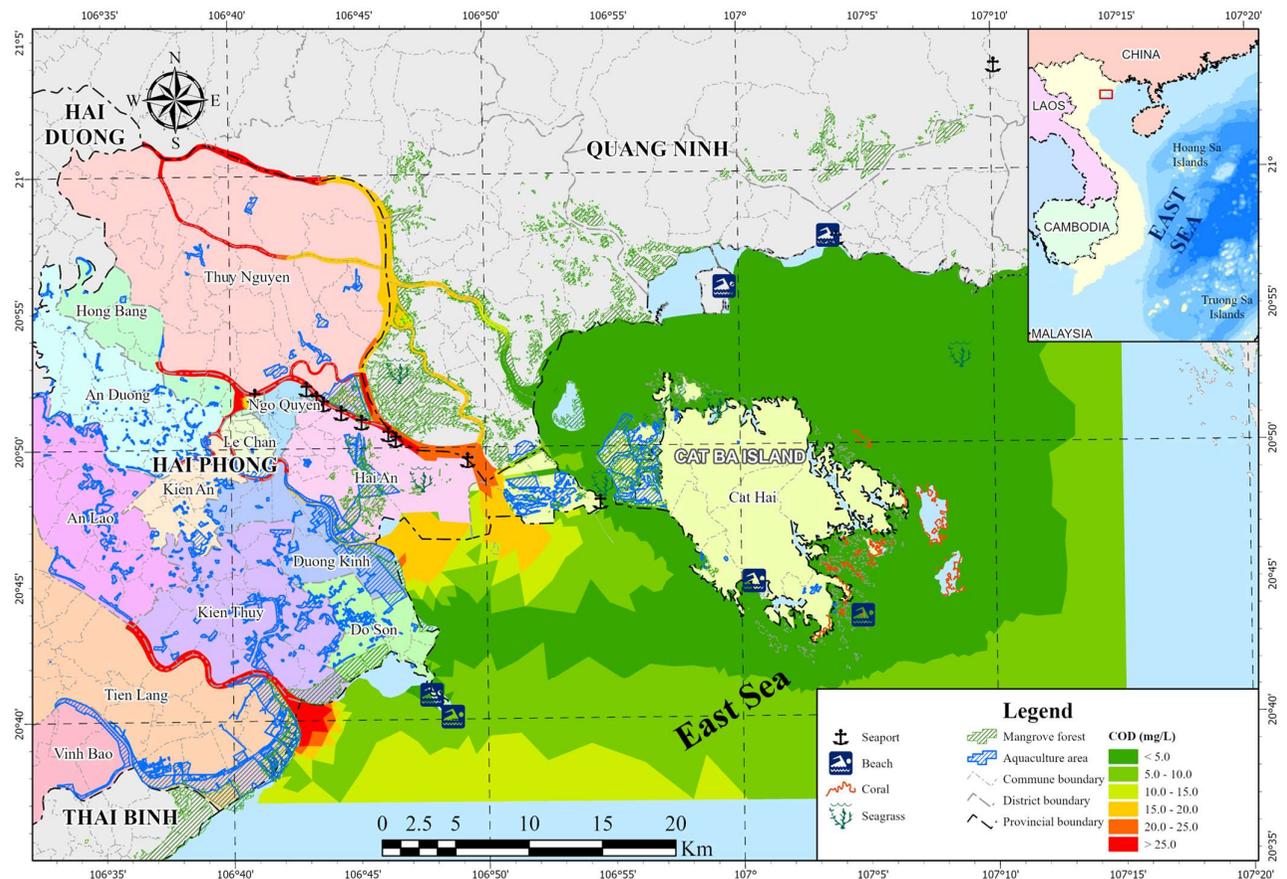

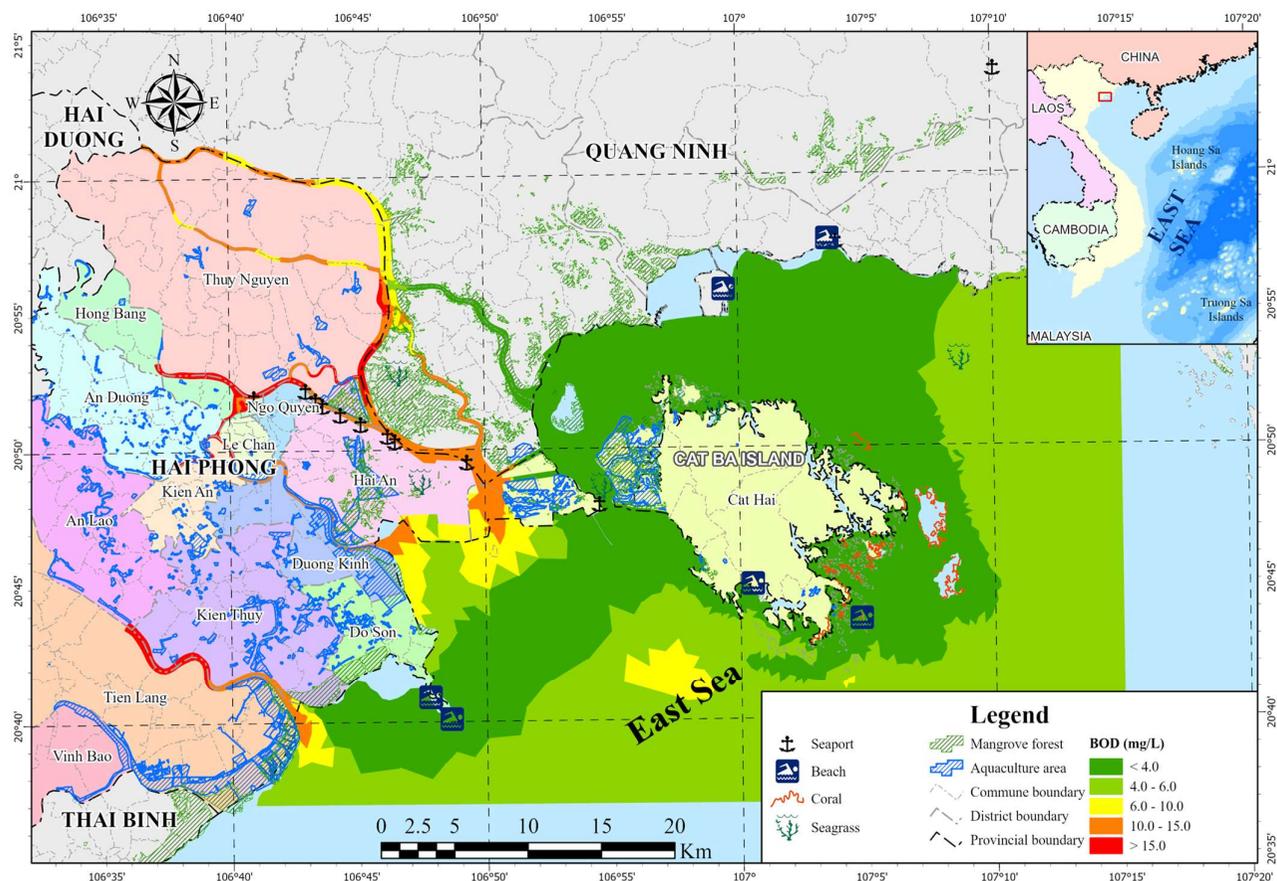Fig. 8: The impact level of COD on the ecosystem in the study area.

Fig. 9: The impact level of BOD$_5$ on the ecosystem in the study area.

TSS content in the water source, the lower the water's clarity. High TSS can reduce the natural dissolved oxygen levels in the water and increase the water temperature. This can hinder aquatic organisms, such as small fish, from surviving. TSS can also block sunlight, potentially halting the photosynthesis process, reducing plant life, and further decreasing oxygen concentrations in the water.

Simulation results show that the TSS concentration in the study area is relatively high, with an average concentration exceeding 20 mg/L. It can be observed that in the future, measures will be needed to control the TSS concentration around areas with concentrated ecosystems in the study area (Fig. 10).

e) *Assessment of the impact of Fe concentration on the ecosystem:* Dissolved metals in water are easily absorbed by aquatic organisms. The metal concentration in the bodies of aquatic species can accumulate over time, surpassing the concentration present in the water. Toxic metals have adverse effects on the survival, activity, development, circulation, and reproduction of organisms. Metals can cause poisoning, harming organisms without directly causing death (Mitra et al. 2022). Simulation results of heavy metal Fe dispersion in the coastal water environment show that the study area is not currently affected by elevated Fe concentrations (Fig. 11).

f) *Assessment of the impact of Coliform concentration on the ecosystem:* Coliform is a type of bacteria that naturally occurs and is present in all human and animal waste. Coliform bacteria in wastewater can indicate the presence of harmful, disease-causing organisms. These organisms are called pathogens and can include viruses, protozoa, or bacteria. The results show that the Coliform concentration ranges from 1000 to 4000 MPN/100mL (Fig. 12). This concentration is within the acceptable limits of Class A to Class B according to QCVN 08:2023.

Development of a Pollution Risk Zoning Map for the Study Area

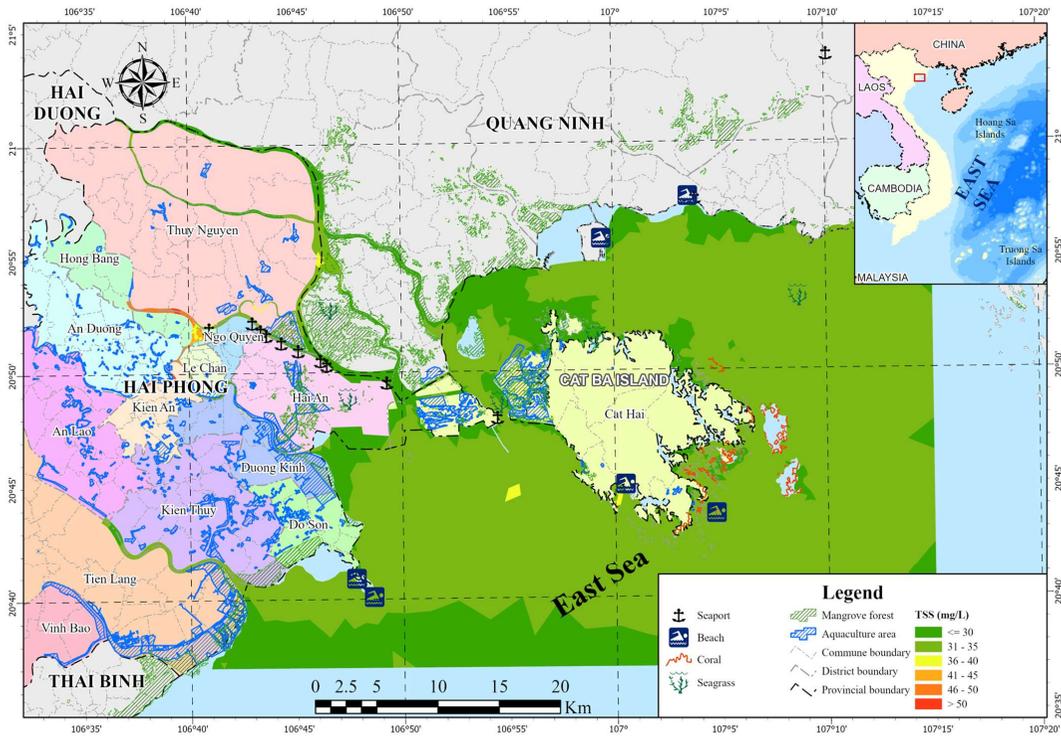To assess the comprehensive impact of coastal pollution on

Fig. 10: The impact level of TSS on the ecosystem in the study area.
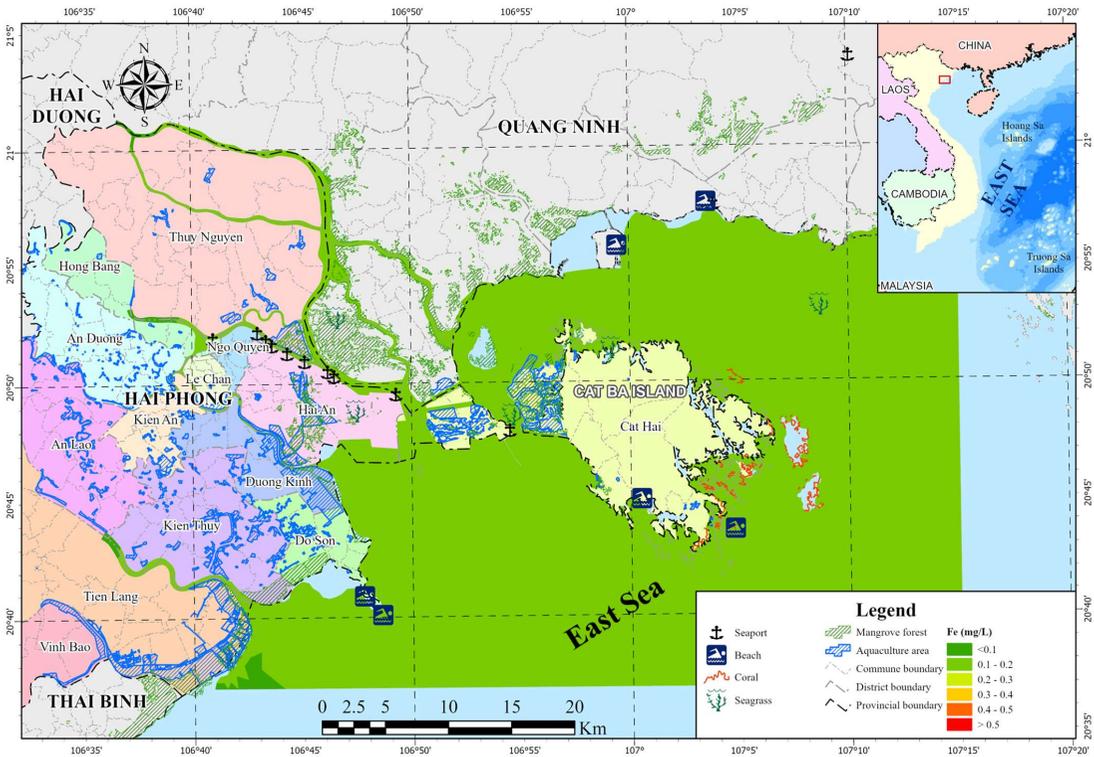

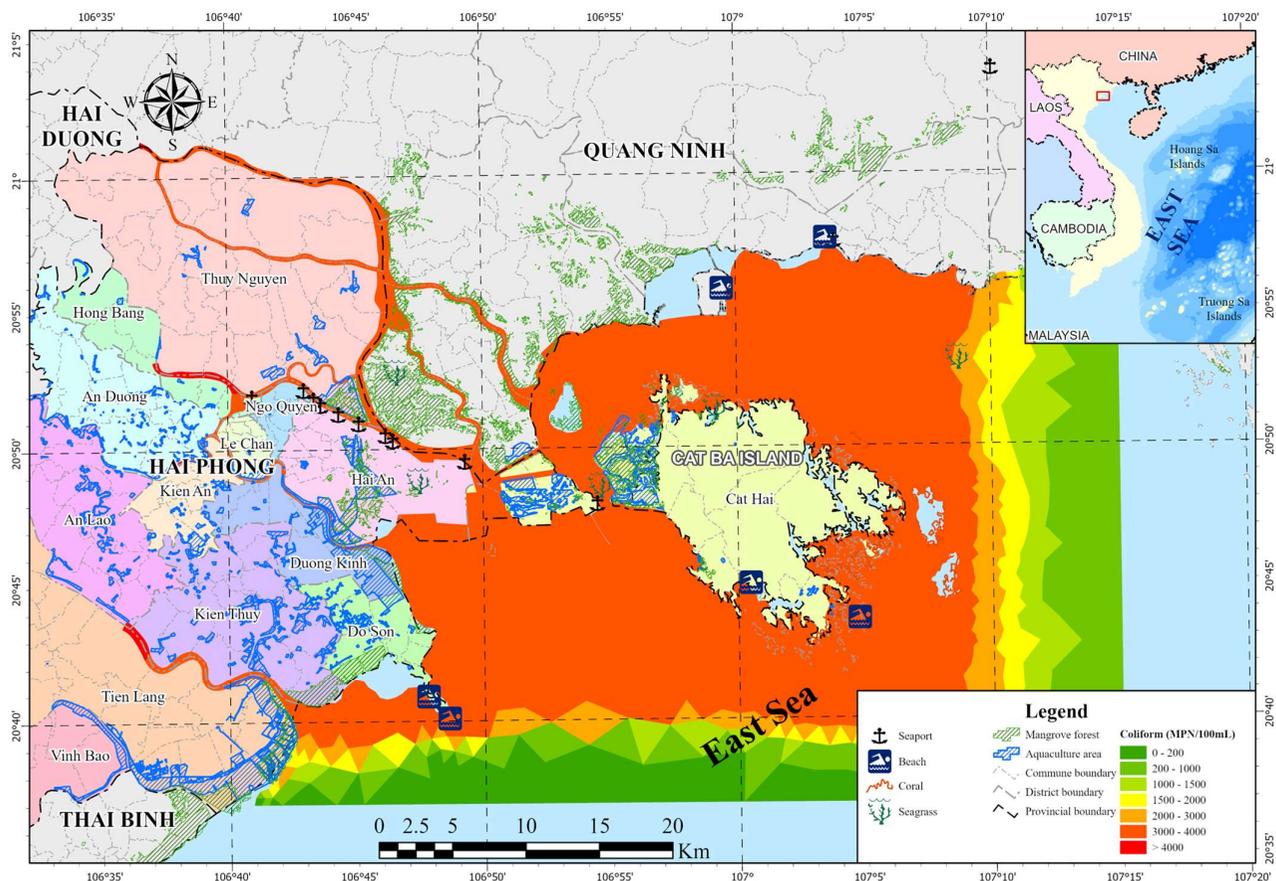Fig. 11: The impact level of Fe on the ecosystem in the study area.

Fig. 12: The impact level of coliform on the ecosystem in the study area.

the marine ecosystem as well as on aquaculture areas, the report developed a pollution risk zoning map. The coastal waters of Hai Phong are divided into areas of water pollution risk, ranging from low to very high environmental pollution risk, according to the environmental risk classification scale (RQ) and are represented by different color scales. The method for assessing the risk of marine water pollution follows Circular No. 26/2016/TT-BTNMT (MoNRE 2016), and the formula for calculating the RQ index is as follows:

$$RQ = \frac{\sum_{j=1}^{m} W_j \left(\dfrac{MEC}{PNEC} \right)_j}{\sum_{j=1}^{m} W_j} \qquad \ldots(1)$$

where MEC is the concentration of pollutant parameter j in the environment, calculated from monitoring data and measurements that comply with the current Vietnamese standards and national technical regulations for assessing environmental quality components and types of pollution; PNEC is the limit concentration of pollutant parameter j in the environment according to current standards (National

Technical Regulation on the quality of coastal, nearshore, and offshore waters - QCVN 10-MT:2023/BTNMT); m is the total number of pollutant parameters being considered and evaluated; W_j is the weight factor used to calculate the risk coefficient for pollutant j, as specified in Clause 4, Article 11 of Circular No. 26/2016/TT-BTNMT (MoNRE 2016) in Table 5.

The pollution level index or the risk of marine and island environmental pollution is based on the average environmental risk index (RQ) of the zones, as specified in

Table 5: The weight factors of the pollution parameters (MoNRE 2016).

No	Pollutant parameters	Weight factor
1	Toxic substances	2.0
	Heavy metals (Fe)	2.0
2	Substances or factors that deplete oxygen in seawater	1.5
	BOD_5, COD, DO	1.5
3	Total coliform	1.3
4	TSS	1.0

Table 6: Criteria for assessing the Environmental Risk Index.

No	Criteria	Environmental Risk Index (RQ)
1	Very high	RQ > 1,5
2	High	1,25 < RQ ≤ 1,5
3	Medium	1 < RQ ≤ 1,25
4	Low	RQ ≤ 1

Clause 2, Article 11 of Circular No. 26/2016/TT-BTNMT (MoNRE 2016) (Table 6).

Based on the simulation results of pollutant parameter dispersion in the study area using the MIKE 21 model, the study calculated the RQ values for the coastal area of Hai Phong and developed a water pollution risk zoning map, as shown in Fig. 13.

The results show that the coastal area has a higher risk of pollution compared to the outer marine area, which is reasonable as the economic and social activities in the coastal area have intensified, increasing the risk of marine water pollution in this region. The coastal marine area of Hai Phong is significantly influenced by pollution from river water, with the most notable source being the discharge from the Bach Dang River. According to recent statistics (Mitra et al.

2022), the Bach Dang River estuary receives a considerable amount of waste each year: about 45,000 tons of COD; 8,100 tons of BOD_5; more than 13,700 tons of total nitrogen (of which about 3,700 tons is dissolved nitrogen); 3,200 tons of total phosphorus (1,200 tons in the form of PO_4^{3-}), and about 106,000 tons of TSS. Among these sources, domestic wastewater accounts for the highest percentage (nearly 41.31%), followed by livestock farming (30.27%), industrial sources (13.5%), and the lowest from aquaculture (2.27%).

The risk zoning map visually represents the potential risk levels for the coastal area of Hai Phong, using color scales to indicate different degrees of risk. This allows users to quickly identify high-risk areas and propose appropriate solutions for each period, aligned with socio-economic development orientations.

Proposed Solutions for the Study Area

Develop and Improve Policies, Laws, and Organizational Structure

(i) Review and propose improvements to policies for controlling marine pollution (for industrial zones, craft villages, aquaculture areas, environmentally sensitive regions, and specific local areas);
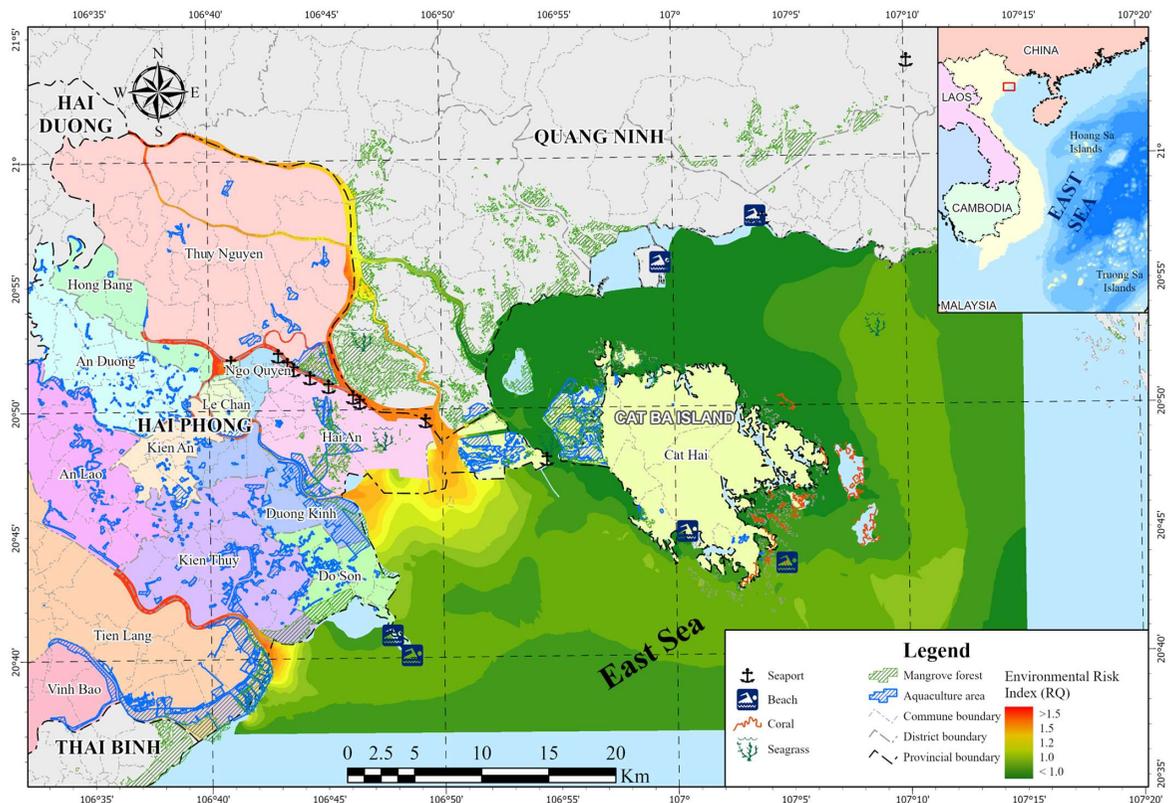

Fig. 13: The risk zoning map for water pollution in the coastal marine area of Hai Phong.

(ii) Develop and issue guidelines for applying marine environmental protection standards (KSONB) locally;

(iii) Create directives and procedures for monitoring and assessing marine pollution;

(iv) Develop technical guidelines (investigation, monitoring, incident response, environmental remediation);

(v) Develop an integrated environmental-communication plan to promote participation in marine-environment protection.

The lead agency for this plan is the Department of Agriculture and Environment of Hai Phong, with participating agencies including the People's Committee and all relevant departments in Hai Phong, and the Department of Marine and Island Affairs.

Strengthen Environmental Investigations and Build a Comprehensive Marine-Environment Information System

(i) Assess marine-environmental risks in the area: identify causes, risk levels, assess data reliability, identify information gaps, and propose improvements to the monitoring program;

(ii) Strengthen equipment at environmental-monitoring stations in Hai Phong;

(iii) Develop a comprehensive marine-environment database (including an updated baseline database and a specialized ATLAS map set);

(iv) Apply digital technologies to create a web platform for marine-environment pollution control.

The lead agency for this plan is the Department of Agriculture and Environment of Hai Phong, with participation from all relevant departments and local People's Committees.

Prevent and Reduce Marine Pollution from Socio-Economic Activities

(i) Review projects and development plans in coastal districts and integrate marine-environmental protection measures;

(ii) Review programs requiring Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA), assess compliance, and list facilities lacking EIA documents or causing serious pollution;

(iii) Strengthen inspections of discharge sources (industrial parks, factories, urban areas, mining zones, aquaculture areas);

(iv) Propose measures for improved monitoring, enforcement, and penalties for non-compliant facilities.

The lead agency for this plan is the Department of Agriculture and Environment of Hai Phong, with participation from all relevant departments and local People's Committees.

Review Pollution Hotspots in Coastal Areas and River Mouths

Identify severely polluted zones and prioritize wastewater collection-and-treatment projects for sources discharging into hotspot areas. Prepare pre-feasibility and feasibility studies and conduct cost-benefit analyses for each project. The lead agency for this plan is the Department of Agriculture and Environment of Hai Phong, with participation from all relevant departments and local People's Committees.

To Control the Risk of Marine Pollution

Strict control of on-site waste by collecting and treating waste at source with particular focus on diffuse emissions such as domestic and agricultural waste entering river and coastal-lake systems. Direct discharges into coastal rivers and lakes, including effluents from industrial zones, craft villages, and seafood-processing facilities, must meet technical standards before release into the environment. Table 7 summarizes the pollutant concentrations used in the mitigation scenario.

After simulating the above scenario, the report the environmental risk index (RQ) and developed a marine-pollution risk map (Fig. 13). The results indicate that if the emission sources are treated as per the simulation scenario, the water quality in the coastal area will improve significantly, and it is noticeable that the area of very high and high environmental pollution risk zones has decreased substantially. Therefore, to ensure sustainable economic development in the coastal city area, the proposed solution is to improve the quality of wastewater treatment plants, reducing the concentration of waste from industrial sources after treatment and discharge into the environment. However, to implement this solution, a balance must be made between the investment in wastewater treatment technology and the

Table 7: Concentration of parameters in the simulation scenario for mitigation.

No	Parameters	Column A concentration (mg/L) (QCVN 40:2011/ BTNMT)	Simulation scenario concentration (mg/L)
1	DO	-	10
2	BOD_5	30	15
3	COD	75	40
4	TSS	50	25
5	Fe	1	0.5
6	Coliform	3000	1500

potential profit from industrial zones and clusters, to establish the most suitable permissible standard thresholds, ensuring the reduction of marine pollution risks while promoting socio-economic development in the research area.

One solution that has gained attention in recent years globally is the reuse of wastewater to promote circular economy development. Wastewater from industrial zones and clusters, after being discharged, is partially treated with simple, low-cost treatment technology and then reused for appropriate purposes within those industrial zones and clusters. The remaining part is treated with advanced technology to meet standards for other uses, while ensuring the maintenance of the current load of receiving water bodies, without putting additional pressure on those receiving sources.

DISCUSSION

The simulation results using the MIKE 21 model reveal significant pollutant dispersion patterns in Hai Phong's coastal waters, with notable concentrations of DO, BOD_5, COD, TSS, Fe, and coliform exceeding permissible limits at multiple sampling locations. Estuarine waters near Dinh Vu - Cat Hai and the Nam Cau Kien industrial zones exhibit the highest pollutant levels, particularly for BOD_5 and COD, indicating strong organic pollution loads from industrial wastewater discharge. These findings align with previous studies (Tri et al. 2019, Vinh et al. 2020, Thu & Tri 2023, Le et al. 2023), which also reported severe water quality degradation in these industrialized coastal areas.

Our results further show that DO levels decrease significantly in pollution hotspots, confirming the impact of high organic loads on oxygen depletion, a key factor contributing to coastal eutrophication (Vinh et al. 2020). Similarly, TSS and Fe concentrations are notably high in areas influenced by industrial runoff and port activities, consistent with findings by Vinh et al. (2020), who highlighted sediment resuspension as a major contributor to metal contamination in Hai Phong's coastal waters.

The environmental pollution risk zoning map, developed based on pollutant dispersion simulations, identifies three high-risk zones where pollution levels are consistently above national water quality standards. These zones correspond to areas with dense industrial activity and limited water circulation, making them more vulnerable to pollution accumulation. This result supports previous assessments by Tran et al. (2018), who emphasized the role of hydrodynamic conditions in determining pollutant retention in coastal ecosystems.

Under projected climate change scenarios, our simulations indicate a shift in pollutant dispersion patterns due to rising sea levels, increased rainfall intensity, and altered hydrodynamic conditions. Higher precipitation rates intensify runoff from industrial areas, leading to increased concentrations of COD, TSS, and coliform bacteria, a trend also observed in studies on urban-industrial coastal regions (Müller et al. 2020). Moreover, extreme weather events, such as storm surges and typhoons, exacerbate pollutant transport, further spreading contaminants into sensitive marine habitats (IPCC 2021).

Interestingly, sea-level rise appears to enhance water circulation in some areas, potentially diluting pollutant concentrations in open waters. However, semi-enclosed coastal zones continue to exhibit high pollutant retention, increasing environmental risks for nearby aquaculture and marine biodiversity (Le et al. 2022, Phu et al. 2022). These findings underscore the necessity of integrating climate adaptation measures into coastal pollution management strategies.

While previous research has primarily focused on monitoring industrial pollution in Hai Phong's coastal areas (Tri et al. 2019, Vinh et al. 2020), limited studies have integrated hydrodynamic modeling with climate change scenarios to assess long-term environmental impacts. Our study fills this gap by applying the MIKE 21 modeling system to simulate wave propagation, hydrodynamics, and pollutant dispersion under various climate projections. Vinh et al. (2020) reported severe water quality degradation near industrial zones but did not assess future climate impacts. Our study extends this by modeling pollutant dispersion under multiple climate change scenarios, providing a more comprehensive risk assessment. Studies focused on water quality trends in industrial coastal areas but did not develop a pollution risk zoning map (Le et al. 2023, Thu & Tri 2023, Nam et al. 2025, Tinh & Quoc 2025). Our research enhances environmental planning by identifying high-risk areas for targeted pollution control measures. Singaraja et al. (2018) examined hydrodynamic influences on pollutant transport but did not incorporate long-term climate projections. Our study addresses this gap by analyzing future climate-induced changes in pollution dispersion patterns. By bridging these knowledge gaps, our findings provide a novel framework for adaptive coastal management, supporting policy development for sustainable environmental protection in Hai Phong and similar industrial coastal regions.

CONCLUSIONS

This study provides an integrated assessment of wave dynamics, hydrodynamic, and water quality in the coastal region of Hai Phong, Vietnam, under the influence of industrial pollution and climate change. The key findings and contributions are outlined as follows:

(1) Model Calibration and Validation: The research successfully calibrated and validated the wave, hydrodynamic, and water quality models using observed field data. This rigorous calibration process ensured the reliability of parameter sets, enabling the models to accurately replicate real-world conditions within the study area. The validated models offer a robust platform for simulating environmental changes and assessing future scenarios. Their credibility lays a strong foundation for analyzing the dispersion of pollutants and evaluating the impacts of human activities and climate variability.

(2) Pollution Impact Assessment under Climate Change Scenarios: The study systematically evaluated the influence of pollutant discharge from key coastal industrial zones in Hai Phong. It explored how pollutants disperse and accumulate in marine environments under various climate change scenarios, including sea level rise, altered river discharge, and increased storm frequency. This analysis underscores the heightened vulnerability of the coastal zone to compounded stressors, offering critical insights into potential shifts in pollution patterns and environmental risks over time. These results provide valuable guidance for anticipating and mitigating adverse ecological impacts due to both anthropogenic and climatic pressures.

(3) Development of Environmental Risk Zoning and Adaptation Strategies: Leveraging simulation results, the study developed an environmental pollution risk zoning map, which identified areas of high, medium, and low risk. This zoning tool is instrumental for environmental planners and decision-makers, offering spatial guidance for targeted monitoring, regulation, and intervention. Additionally, the study proposed adaptive strategies for sustainable ecosystem management, including regulatory frameworks, pollution control technologies, and ecological restoration measures aimed at enhancing the resilience of coastal ecosystems.

Despite its contributions, the study has some limitations that suggest directions for future research:

(1) Incorporation of Long-Term Climate Projections: While the study considered climate change scenarios, it lacked a comprehensive integration of long-term climate projections. Future research should extend simulations to mid- and late-century timeframes (e.g., 2050–2100) using high-resolution downscaled climate models to enhance the predictive capacity and support long-term planning.

(2) Assessment of Socioeconomic Impacts: The current focus is predominantly environmental. However, the socioeconomic dimensions of pollution such as impacts on fisheries, aquaculture, public health, and local livelihoods remain underexplored. Including these aspects would offer a more holistic understanding of risks and support the formulation of integrated adaptation strategies.

(3) Marine Biodiversity and Ecosystem Resilience: Further studies should examine the resilience and adaptability of marine species and ecosystems in polluted environments. Identifying ecological thresholds for degradation would be critical for developing biodiversity conservation plans and setting regulatory limits for pollutant discharge.

By addressing these gaps, future research can build a more comprehensive framework for coastal environmental management, balancing ecological sustainability with economic development under changing climatic conditions.

ACKNOWLEDGMENTS

REFERENCES

Anh, P.T., Kroeze, C., Bush, S.R. and Mol, A.P.J. 2010. Water pollution by Pangasius production in the Mekong Delta, Vietnam: causes and options for control. *Aquaculture Research*, 42(1), pp.1–21. [DOI]
Chang, J.I., Kim, G., Park, D.U., Shin, W. and Choi, I. 2024. Development of Ocean Economy Satellite Accounts for the Coastal and Marine Tourism Sector in Korea. *Journal of Coastal Research*, 116(sp1), pp.373–377. [DOI]
Dai, T., Su, Z., Zeng, Y., Bao, Y., Zheng, Y., Guo, H., Yang, Y. and Wen, D. 2023. Wastewater treatment plant effluent discharge decreases bacterial community diversity and network complexity in urbanized coastal sediment. *Environmental Pollution*, 322, pp.121122. [DOI]
Dieu, L.V. 2015. Final Report on the Research Project: Assessment of the Environmental Carrying Capacity of Selected Coastal Water Bodies in Vietnam for Sustainable Development (Code: KC 09.17/11-15), *Institute of Marine Resources and Environment*.
DHI, 2014a. Nearshore Spectral Wind-Wave Module, User Guide, MIKE 21 (SW), Denmark.
DHI, 2014b. Hydrodynamic Module, User Guide, MIKE 21 (FM), Denmark.
DHI, 2014c. Hydrodynamic Module, Scientific Documentation, MIKE 21 (FM), Denmark.
DHI, 2014d. MIKE 21 Toolbox, User Guide, Denmark.
DHI, 2014e. MIKE 21 Toolbox, User Guide, Denmark.
DHI, 2014f. EcoLab Short Scientific Documentation, MIKE 21/3 (WQ), Denmark.
DHI, 2014g. MIKE 21 EcoLab User Guide, Denmark.
DHI, 2014h. MIKE 21 EcoLab Water Quality Module, Denmark.
DHI, 2014i. MIKE 21 EcoLab Heavy Metal Transport Module, Denmark.

Dao, N.V. 2023. Study on the Assessment of Salinity Intrusion Risk in the Coastal Areas of Thai Binh–Nam Dinh Under Different Scenarios of Tidal and Sea Level Rise. Doctoral Thesis in Engineering, *Thuyloi University*, p.222. (in Vietnamese)

Duong, T.N. and Le, V.N. 2019. Coastal Water Quality in the Northern Part of Vietnam. *Vietnam Journal of Marine Science and Technology*, 19, pp.89–102. (in Vietnamese)

Duong, T.N., Le, V.N., Pham, T.K., Le, X.S., Dinh, H.N. and Cao, T.T.T. 2020. Water Environment Quality at Coastal Monitoring Stations in Vietnam (2019). *Vietnam Journal of Chemistry*, 58, pp.147–152. (in Vietnamese)

El-Sharkawy, M., Alotaibi, M.O., Li, J., Du, D. and Mahmoud, E. 2025. Heavy Metal Pollution in Coastal Environments: Ecological Implications and Management Strategies. *Sustainability*, 17, p.701. [DOI]

Hai, N.M. and Vinh, V.D. 2021. Simulation of impact of organic and nutrient pollutants from Nghi Son economic zone on Thanh Hoa coastal waters, North Centre Vietnam. *Aquaculture Research*, 42(1), pp.1–21. [DOI]

Hai, N.M., Vinh, V.D., Ouillon, S., Lan, T.D. and Duong, N.T. 2025. Modelling Impacts of Climate Change and Anthropogenic Activities on Ecosystem State Variables of Water Quality in the Cat Ba–Ha Long Coastal Area (Vietnam). *Water*, 17, p.319. [DOI]

Hidayati, D., Syauqa, R.A.A., Saptarini, D., Payus, C.M., Syahroni, N. and Mulyadi, Y. 2025. The Saprobic Index for Water Quality Based on Fish Aquaculture: A Case Study of White Snapper (Lates calcarifer) in Floating Net Cages at Sendang Biru Water, Indonesia. *Nature Environment and Pollution Technology*, 24(1), pp.1–8. [DOI]

Gomes, M.P. 2024. The Convergence of Antibiotic Contamination, Resistance, and Climate Dynamics in Freshwater Ecosystems. *Water*, 16, p.2606. [DOI]

Khac, H.N. 2020. Research on Smart Coastal Aquaculture Development Solutions Adapted to Climate Change in the Northern and North Central Coastal Regions, National-Level Project, Code BĐKH.18/16-20. (in Vietnamese)

IPCC, 2021. *Climate Change 2021: The Physical Science Basis*, Intergovernmental Panel on Climate Change, Working Group I Contribution to the Sixth Assessment Report. *Cambridge University Press*. [DOI]

Jin, L., Ding, L., Zhang, Y., Li, T. and Liu, Q. 2025. Profiling heavy metals distribution in surface sediments from the perspective of coastal industrial structure and their impacts on bacterial communities. *Ecotoxicology and Environmental Safety*, 294, p.118098. [DOI]

Le, T.V., Do, D.D. and Nguyen, B. 2023a. Spatiotemporal Assessment and Pollution-Source Identification and Quantification of the Surface Water System in a Coastal Region of Vietnam. *Hydrological Sciences Journal*, 68, pp.782–793. [DOI]

Le, T.V., Nguyen, D.T.P. and Nguyen, B.T. 2023b. Spatial and Temporal Analysis and Quantification of Pollution Sources of the Surface Water Quality in a Coastal Province in Vietnam. *Environmental Monitoring and Assessment*, 195, p.408. [DOI]

Le, N.D., Hoang, T.T.H., Phung, V.P., Rochelle-Newall, E., Duong, T.T., Pham, T.M.H., Phung, T.X.B., Nguyen, T.D., Le, P.T., Pham, L.A., Nguyen, T.A.H., Le, T.P.Q. and Nguyen, T.A.H. 2022. Evaluation of heavy metal contamination in the coastal aquaculture zone of the Red River Delta, Vietnam. *Chemosphere*, 303, p.134952. [DOI]

Maddah, H.A. 2022. Predicting Optimum Dilution Factors for BOD_5 Sampling and Desired Dissolved Oxygen for Controlling Organic Contamination in Various Wastewaters. *International Journal of Chemical Engineering*, 8637064, pp.1–14. [DOI]

Ministry of Natural Resources and Environment (MoNRE), 2020. Climate Change Scenarios.

MoNRE, 2013. Plan for Marine Environmental Pollution Control in the Quang Ninh–Hai Phong Area.

MoNRE, 2016. Circular on Detailed Regulations on Criteria for Zoning Marine and Island Environmental Pollution Risks and Guidelines for Zoning Marine and Island Environmental Pollution Risks.

Mitra, S., Chakraborty, A.J., Tareq, A.M., Emran, T.B., Nainu, F., Khusro, A., Idris, A.M., Khandaker, M.U., Osman, H., Ilhumaydhi, F.A. and Simal-Gandara, J. 2022. Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. *Journal of King Saud University – Science*, 34(3), p.101865. [DOI]

Müller, A., Österlund, H., Marsalek, J. and Viklander, M. 2020. The pollution conveyed by urban runoff: A review of sources. *Science of The Total Environment*, 709, p.136125. [DOI]

Nam, L.V., Luu, N.T.M., Sinh, L.X., Nghi, D.T., Kha, P.T., Trang, C.T.T., Nhon, D.H., Bach, N.V., Ha, N.T.T. and Chi, D.T.K. 2025. Development of a water quality index to assess and classify water quality in the coastal waters of Hai Phong (Vietnam). *Vietnam Journal of Marine Science and Technology*, 25(1), pp.87–102. [DOI]

Nguyen, D.T., Pham, T.T. and Tang, T.K.H. 2024. Biodiversity status of the Mekong Delta, Vietnam. CIFOR–ICRAF Working Paper 31, pp.1–34. *Bogor: CIFOR and Nairobi: ICRAF*. [DOI]

Oladimeji, T.E., Oyedemi, M., Emetere, M.E., Agboola, O., Adeoye, J.B. and Odunlami, O.A. 2024. Review on the impact of heavy metals from industrial wastewater effluent and removal technologies. *Heliyon*, 10(23), Article e40370. [DOI]

Sharma, D., Rao, K. and Ramanathan, A.L. 2021. A systematic review on the impact of urbanization and industrialization on the Indian coastal mangrove ecosystem. In: Madhav, S., Nazneen, S. and Singh, P. (eds.), *Coastal Ecosystems*, Coastal Research Library 38. *Springer, Cham*, pp.175–199. [DOI]

Singh, B.J., Chakraborty, A. and Sehgal, R. 2023. A systematic review of industrial wastewater management: Evaluating challenges and enablers. *Journal of Environmental Management*, 348, p.119230. [DOI]

Singaraja, C., Chidambaram, S. and Jacob, N. 2018. A study on the influence of tides on the water table conditions of shallow coastal aquifers. *Applied Water Science*, 8, Article 11. [DOI]

Sun, X., Yang, R., Ji, J., Zhu, Z., White, J.C. and Shen, Y. 2024. An evaluation of microplastic contamination in the marine waters and species in the coastal region of the South Yellow Sea, China. *Journal of Hazardous Materials*, 469, Article 134018. [DOI]

Pascoe, S., Paredes, S. and Coglan, L. 2023. The Indirect Economic Contribution of Fisheries to Coastal Communities Through Tourism. *Fishes*, 8(3), Article 138. [DOI]

Phu, L.H., Kim-Hong, P.T., Chung, T.V., Binh, T.V., Dung, L.T., Ngoc, P.H., Thu, N.H., Thu, N.T.T., Anh, N.T.H., Nguyen, A.L. and Minh-Thu, P. 2022. Environmental Concerns for Sustainable Mariculture in Coastal Waters of South-Central Vietnam. *Sustainability*, 14, Article 8126. [DOI]

Phuong, T.T.M. 2014. Bioaccumulation of heavy metals in Nha Trang bay, Khanh Hoa, Vietnam. *Earth Sciences*. Doctoral Thesis, Université Nice Sophia Antipolis, p.234. [DOI]

Tran, T.A.M., Leermakers, M., Hoang, T.L., Nguyen, V.H. and Elskens, M. 2018. Metals and arsenic in sediment and fish from Cau Hai lagoon in Vietnam: Ecological and human health risks. *Chemosphere*, 210, pp.175–182. [DOI]

Thu, P.T.S. and Tri, D.Q. 2023. Assessing the Impact of Industrial Zones on the Environmental Pollution in Hai Phong's Coastal Areas, Vietnam. *Journal of Geoscience and Environment Protection*, 11, pp.11–29. [DOI]

Thu, P.T.S., Tri, D.Q. and Hong, N.V. 2023. Application of MIKE 21 model and GIS technology to establish maps and assess the spread of water environment pollution under climate change scenarios for the coastal aquaculture area of Hai Phong. *Journal of Climate Change Science*, 28, pp.1–18. [DOI]

Tong, N.X., Thao, N.T.T. and Anh, L.H. 2024. Assessment of water quality,

heavy metal pollution and human health risks in the canal system of Ho Chi Minh City, Vietnam. *Environmental Research Communications*, 6, Article 075007, pp.1–16. [DOI]

Tri, D.Q., Linh, N.T.M., Tuyet, Q.T.T., Phuong, T.A. and Don, N.C. 2019. Assessment of water quality in coastal estuaries under the impact of an industrial zone in Hai Phong, Vietnam. *Physics and Chemistry of the Earth, Parts A/B/C*, 113, pp.100–114. [DOI]

Tinh, N.T.H. and Quoc, T.B. 2025. Assessment of Heavy Metal Contamination and Sources in Road Dust from the Da Nang's Largest Industrial Zone and Surrounding Areas. *VNU Journal of Science: Earth and Environmental Sciences*, pp.1–16. [DOI]

Tri, D.Q. Assessment of water quality in coastal estuaries under the impact of an industrial zone in Hai Phong, Vietnam [DOI]

Trinh, L., 2017. Water pollution in The Mekong Delta: sources, present, future, ecological impacts and mitigation. *International Water Forum*, Chungnam, Korea, 17–20 October 2017.

Vinh, V.D., Hai, N.M. and Khanh, D.G. 2020. Impacts of pollution discharges from Dinh Vu industrial zone on water quality in the Hai Phong coastal area. *Vietnam Journal of Marine Science and Technology*, 20(2), pp.173–187. [DOI]

Wang, P., Du, P., Sardar, M.F., Chen, Y. and Zhang, Y. 2025. Profiling heavy metals distribution in surface sediments from the perspective of coastal industrial structure and their impacts on bacterial communities, South Yellow Sea, China. *Ecotoxicology and Environmental Safety*, 289, p.117650. [DOI]

Wang, H., Yang, *J*., Wu, *H*. and Niu, *C*. 2024. Research on the impact of marine economic development in coastal areas on regional economic resilience: Evidence from China. *Frontiers in Marine Science*, 11, Article 1414663. [DOI]

Wang, Y., Khan, S.U., Kong, D., Xu, R. and Zhang, Y. 2025. Navigating the dual currents: Advanced insights into carbon emissions and economic growth in China's coastal marine fisheries. *Marine Policy*, 177, Article 106671. [DOI]

Whitehead, P.G., Jin, L., Bussi, G., Voepel, H.E., Darby, S.E., Vasilopoulos, G., Manley, R., Rodda, H., Hutton, C., Hackney, C., Tri, V.P.D. and Hung, N.N. 2019. Water quality modelling of the Mekong River basin: Climate change and socioeconomics drive flow and nutrient flux changes to the Mekong Delta. *Science of The Total Environment*, 673, pp.218–229. [DOI]

Zhang, X., Yun, X., Huang, Y., Shen, G. and Lin, N. 2025. Accounting for microorganisms yields stricter water quality criteria and elevated ecological risks of antibiotics: A case study of sulfonamides in the Yangtze River Delta. *Ecotoxicology and Environmental Safety*, 289, p.117650. [DOI]