MINISTRY OF EDUCATION AND TRAINING

VIETNAM ACADEMY OF SCIENCE AND TECHNOLOGY

GRADUATE UNIVERSITY OF SCIENCE AND TECHNOLOGY

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RESEARCH ON THE IMPACT OF SOCIO-ECONOMIC ACTIVITIES AND CLIMATE CHANGE ON THE COASTAL WATER ENVIRONMENT OF CAT BA - HA LONG

SUMMARY OF DISSERTATION ON ENVIRONMENTAL AND RESOURCE MANAGEMENT

Major: Environmental and Resource Management

Code: 9850101

Hai Phong - 2025

The dissertation is completed at: Graduate University of Science and Technology, Vietnam Academy Science and Technology

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The dissertation is examined by Examination Board of Graduate University of Science and Technology, Vietnam Academy of Science and Technology at……………………….. (time, date……)

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INTRODUCTION

1. The urgency of the thesis

With a coastline stretching over 3260km and more than 1 million km^2 of continental shelf area, our country has very favorable conditions for marine economic development such as cargo transportation, service tourism, and aquaculture exploitation. After the renovation period, our country's socio-economic has developed rapidly, especially in coastal areas. However, the rapid socio-economic development in recent years has been causing great pressures on the marine environment. Among them, the main issue is the significant increase in waste through river mouths, from the discharge sources of production facilities, coastal tourism services, and coastal and surface aquaculture activities.

The quality of aquatic habitats in numerous coastal regions of our country has been significantly compromised, not only owing to environmental incidents but also as a result of pollution sources linked to recent socio-economic development.

Besides the pressure from the increasing pollution caused by human socio-economic activities in coastal areas. This area is also affected by climate change, with increasingly clear manifestations, especially sea level rise (SLR) and rising temperatures. Meanwhile, the increase in temperature can affect the material metabolism, biogeochemical processes, as well as water quality in coastal areas. This consequently elevates the risk of contamination and deteriorates the water quality in the coastal river mouth regions of Vietnam.

The Cat Ba-Ha Long area (CB-HL) is a marine region encompassing the World Heritage natural and geological site of Ha Long Bay and the Cat Ba World Biosphere Reserve. The Cat Ba Archipelago and Ha Long Bay were designated as a UNESCO World Natural Heritage site in September 2023. In recent years, the socio-economic advancement of Quang Ninh province and Hai Phong city, specifically the CB-HL area, has accelerated significantly. These two locales serve as significant growth poles within the development triangle of the Northern Key Economic Region, featuring a concentration of essential economic sectors like coal mining, ports and waterways, tourism services, aquaculture, and seafood processing and exploitation. Nonetheless, that development has intensified the conflict between economic expansion and the preservation of the region's maritime resources and environmental landscape. The degradation of water quality, heightened sedimentation, depletion of resources and biodiversity, and disturbance of landscapes are significant concerns.

While there have been environmental studies in this region, they were undertaken a considerable time ago, when the socio-economic conditions were significantly less advanced than they are today. The manifestations of climate change (CC) are becoming increasingly apparent. Therefore, the integrated effects of human socio-economic activity and CC will intensify in the near future. Consequently, in addition to the exploitation for socio-economic advancement, the management and safeguarding of the aquatic environment for sustainable development are becoming increasingly imperative. What is the present impact of human socio-economic activities on the marine environment in the CB-HL coastal area? What will be the effects of CC in the near future, as well as the combined effects of socio-economic activities and CC on the region's water environment? Responding to the aforementioned enquiries will establish a foundation for recommending management strategies to alleviate the effects of human socio-economic activities and CC on the regional water environment.

In response to that situation, the thesis topic "Research on the impact of Socio-Economic Activities and Climate Change on the Coastal Water Environment of Cat Ba-Ha Long" has been initiated with specific objectives and content.

2. The objectives of the thesis: Assess/predict the impacts of organic and nutrient pollution sources from human socio-economic activities and CC on the water quality of the CB-HL coastal area.

3. The main contents of the thesis

- Theoretical basis and research methods;
- Collect and compile relevant documents in the research area;
- Analyze and evaluate the natural, socio-economic, environmental conditions, and manifestations of CC in the CB-HL coastal area;
- Evaluate the sources of pollutants from human socio-economic activities and their impact on the water environment of the CB-HL coastal area;
- Forecast the impacts of increased pollution sources from human socio-economic activities and CC on the water environment of the CB-HL coastal area;
- Propose management solutions to mitigate the effects of human socio-economic activities and CC on the water environment in the CB-HL area.

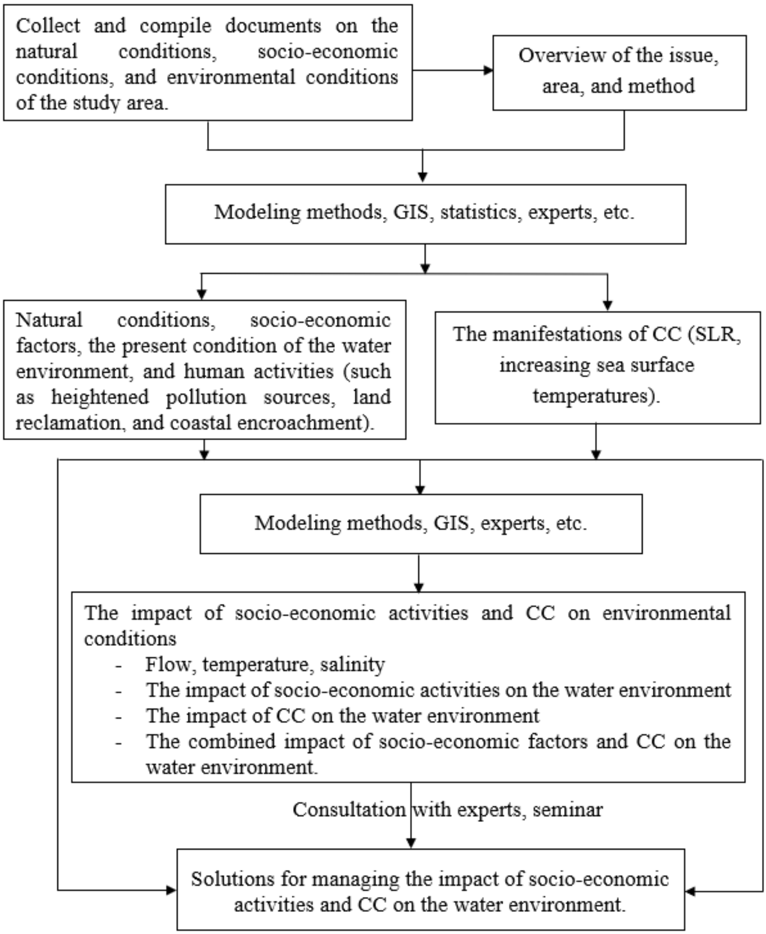

Diagram summarizing the content and research methods

4. Research scope and subjects

Spatial scope: The research area of the thesis focuses on the coastal waters of CB-HL and its surroundings (Figure 1.1), including the origin of pollution sources due to human socio-economic activities.

Research issue: Analysing and evaluating the impact of socio-economic activities and CC on water quality in the CB-HL coastal area.

Research subjects:

- Pollutants (nutrients: NH_4^+, NO_3^-, PO_4^{3-}; organic pollution indicators: BOD, COD) and dissolved oxygen (DO).

-Some socio-economic activities of humans, sources of pollutants;

- The increase in temperature and SLR due to CC in the CB-HL region;

- The processes of spreading and dispersing pollutants from emission sources and their impact on the water environment in the CB-HL area.

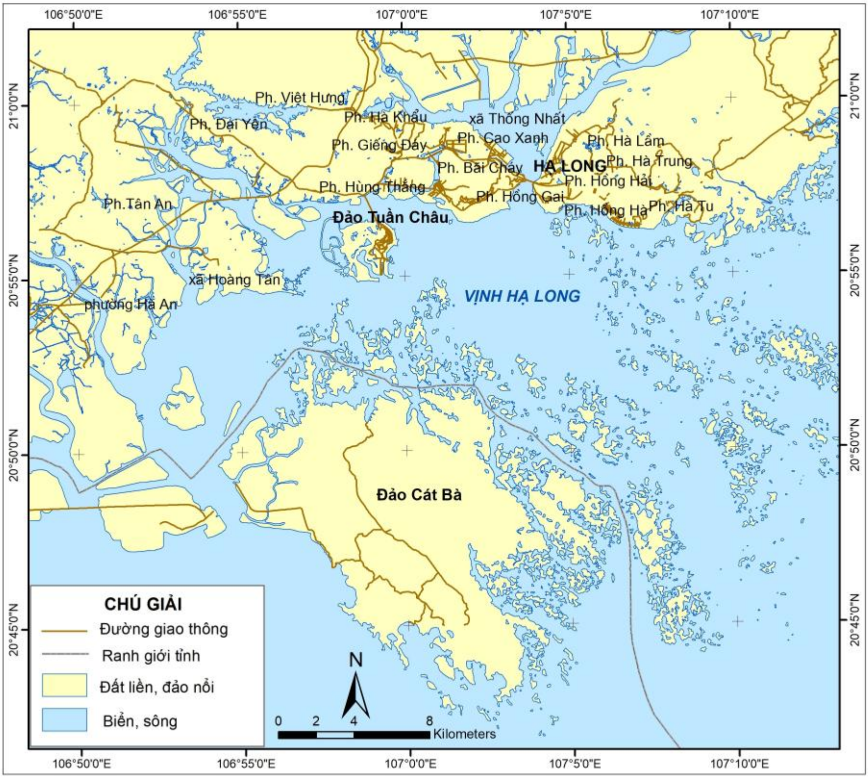

Figure 1.1. Cat Ba - Ha Long coastal area

5. The scientific and practical significance

Scientific significance: The modelling method's application transcends the challenging constraints of traditional survey methods. This study is the inaugural application of a 3D model to investigate and predict the combined effects of socio-economic activities and CC on the water environment of the CB-HL coastal region.

Practical significance: The thesis demonstrates the spatial and temporal variations in water quality in the CB-HL coastal region through the application of mathematical models. This will provide the foundation for developing socio-economic policies related to water environment protection and CC adaptation.

6. New finding of the thesis

- Manifestations of climate change (sea level rise and sea temperature increase) in CB-HL waters based on analysis results from the latest monitoring data to 2020 (the time of implementation of the thesis).

-Separate/combined impacts of socio-economic activities (increasing pollution sources and sea encroachment) and climate change (sea level rise and temperature increase) on the water quality of CB-HL waters based on the calculation/forecast results of the numerical model.

7. The structure of thesis

Besides the introduction, conclusion, and references, the thesis is structured into three main chapters as follows:

Chapter 1. Overview of the issue and research area: provides an overview of the impact of socio-economic activities and CC on the water environment, as well as information on the natural and socio-economic conditions and the present state of water quality in the research area.

Chapter 2 delineates the literature, approach, and research methods to address the objectives in the thesis.

Chapter 3 presents all the research results, including the findings on CC manifestations in the CB-HL area, focusing on the trends of rising sea levels and increasing temperatures based on observational data; the impact of socio-economic activities and CC on environmental conditions and water environments in the CB-HL coastal area under different scenarios such as land reclamation, heightened pollution sources, and the effects of climate change. Based on the analysis, evaluation, and forecasting of the impacts (both individual and integrated) propose environmental management solutions in the CB-HL area.

CHAPTER 1. OVERVIEW

1.1. Overview of the impact of socio-economic activities and climate change on the water environment

1.1.1. Overview of the impact of socio-economic activities on the water environment

1.1.1.1. Research on the impact of socio-economic activities on the coastal water environment worldwide

Human socio-economic activities have adversely affected the environment in coastal areas, causing greater harm to ecosystems than natural phenomena. Temperature increases, SLR, and declining pH are alterations in the coastal environment.

1.1.1.2. Research on the impact of human activities on the coastal water environment in Vietnam

Since the 1990s, scholarly attention has focused on the effects of human socio-economic activities on climate change, based on survey results, analysis, and calculations. Recently, the swift advancement of computational tools and the enhanced capacity for data sharing over the internet have markedly progressed the application of mathematical models in water quality research.

1.1.2. Overview of the synergistic impact of socio-economic activities and climate change

1.1.2.1. Manifestations of climate change around the world

CC is one of the greatest challenges facing humanity in the 21st century, with the most evident manifestations being rising temperatures and sea level rise. According to the IPCC, by the end of the 21st century, temperatures will increase by 1.1 to 2.6°C (RCP4.5) and 2.6 to 4.8°C (RCP8.5) compared to the average during the period 1986-2005.

The global mean sea level (GMSL) is increasing, with an accelerating rate observed in recent decades: 3.16 mm/yr from 1993 to 2015; 3.6 mm/yr from 2006 to 2015.

1.1.2.2. The manifestations of climate change in Vietnam

The analysis results from the data of the Ministry of Natural Resources and Environment indicate an upward trend in both the highest and lowest annual temperatures. The annual temperature increases by approximately 1.5-2.4°C and 3.0-4.2°C according to the RCP4.5 and RCP8.5 scenarios, respectively. Sea levels exhibit a distinct increasing trend at 11 of 15 locations, with an average growth rate of approximately 2.7 mm/yr.

1.1.2.3. The synergistic effects of socio-economic activities and climate change on the world's water environment

Numerous studies worldwide have demonstrated that evaluating the cumulative impact of human socio-economic development and CC is inherently complex, particularly in coastal regions. Therefore, a comprehensive approach is needed, taking into account the interactions between natural conditions, the environment, and socio-economic factors.

1.1.2.4. The synergistic effects of human activities and climate change on water environments in Vietnam

In Vietnam, there has yet to be any research utilising modelling tools to assess the integrated impact of human socio-economic activities and CC on the water environment in coastal river estuary areas.

1.2. Natural, socio-economic conditions and the environment of the research area

1.2.1. Natural conditions

1.2.1.1. Location, terrain of the study area

The CB-HL coastal area is located in the Northeastern of Vietnam. The terrain of the CB-HL area is characterized by the division of approximately 2367 large and small islands. The depth in the area varies mainly between 3-10m, with depths of 10-20m appearing in narrow channels.

1.2.1.2. Climate characteristics

The research area exhibits a tropical monsoon climate, characterized by two distinct seasons: the summer season (May to October) is marked by high temperatures and humidity, accompanied by prolonged heavy rainfall, frequent storms, and thunderstorms; the winter season (November to March) is characterized by cooler, drier conditions with minimal precipitation. The summer season, characterized by an average monthly temperature surpassing 27.7°C, extends from June to September. During the cold winter, the region is often influenced by Northeast monsoon winds, resulting in temperatures falling below 18.5°C.

1.2.1.3. Oceanographic characteristics

The CB-HL coastal area is influenced by diurnal tide regime with a maximum tidal range of 4.6 meters. Each month features two spring tide periods with an average water level of 3.9 m, and two neap tide periods.

The flow field of the CB-HL sea area is a composite flow closely linked to tide variations, wind patterns, and the impact of river water masses entering the region.

The sea waves in the research area are typically small, with the exception of storm waves, and the frequency of calm waves is 28.2%. In the winter season, the dominant wave direction is East/Northeast, with an average wave height of 0.5 to 0.6 meters. During summer, the mean wave height ranges from 0.6 to 0.8 meters, with waves primarily originating from the Southeast at a frequency of 27% and from the South at a frequency of 22%.

1.2.2. Socio-economic characteristics related to water quality in the study area

1.2.2.1. Aquaculture and fishing activities

Aquaculture and fishing are important economic activities. The aggregate production of fishing and aquaculture in Hai Phong and Quang Ninh has been rising throughout the years.

1.2.2.2. Tourism activities

Tourism and services are also an important and key economic sector in this area. Nonetheless, tourism presents considerable challenges to the conservation of heritage values and world wonders.

1.2.2.3. Industrial production activities

Hai Phong City and Quang Ninh are two regions with high industrial production value. The coastal industrial zones and clusters are advancing swiftly and have already impacted the marine environment of the region.

1.2.2.4. Coastal urbanization activities

Urban wastewater constitutes a significant source of water pollution in the CB-HL coastal area. The current volume of wastewater discharged into Ha Long Bay is approximately 15,300 m^3/day; however, the volume of treated water released into the sea remains significantly inadequate.

Alongside the waste produced by urbanization in coastal areas, land reclamation activities are also transforming the environment in the CB-HL coastal region. Over the past decade, the Cua Luc Bay has undergone reclamation encompassing a total of 419.2 hectares. In the coastal region of Bai Chay-Tuan Chau, the water surface area was 4,770.3 hectares prior to 2010; however, due to extensive land reclamation efforts in subsequent years, by 2019, it had diminished to 3,546.1 hectares, representing a decrease of 1,224.2 hectares.

1.2.3. Current status of water environmental quality

1.2.3.1. Dissolved oxygen

1.2.3.2. Soluble nutrition

1.2.3.3. Organic compounds

1.2.3.4. Suspended sediment

The examination of the water environment status in the area indicates that the majority of pollutants comply with the allowed limits according to QCVN10:2023/BTNMT. Nonetheless, there are indications of localized contamination near discharge sources at specific times.

CHAPTER 2. RESEARCH METHODS AND MATERIALS

2.1. Material

The following document groups have been used, including:
- Socio-economic data from the statistical yearbook of Quang Ninh province and Hai Phong city for the years 2018-2023

- Water level data from Hon Dau station (1961-2020), Bai Chay station (1981-2020), and temperature data from both Hon Dau and Bai Chay stations (1995-2000).

- The depth and shoreline data for the research region were digitized using UTM topographic maps utilizing the VN 2000 geographic coordinate system at scales of 1:50,000 and 1:25,000, as well as the GEBCO-1/8 database from the UK Hydrographic Office.

- The tidal harmonic constants of 13 tidal constituents are: M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, MF, MM, M_4, MS_4, MN_4, derived from the TPXO8 global tidal model database, which has a spatial resolution 0.25° x 0.25°.

- Meteorological data: meteorological field data for the entire study area sourced from ECMWF Re-analysis-5 (ERA5).

- Hydrological records of the river at some hydrological stations in the region, including Cua Cam, Trung Trang, and Quyet Chien.

- The survey data on pollutants from projects NĐT.97.BE/20 and VAST05.05/21-22 are The thesis has acquired a comprehensive and systematic collection of documents, data, and significant measurement, survey, and research findings.utilized to calibrate and validate the model.

- Total pollutant load in 2019 and forecast for 2030 in the CB-HL area from the projects NĐT.97.BE/20.

According to the defined objectives, the thesis research encompasses five primary issue groups organized according to a problem-solving framework, which include: 1) Overview of the effects of socio-economic activities and climate change on water environments; 2) Collection and synthesis of relevant documents; 3) Assessment of climate change manifestations in the research area; 4) Assessment of the influence of socio-economic activities and climate change on water environments; 5) Proposing management solutions for the impact of socio-economic activities and climate change on water environments.

2.2. Approach

2.2.1. System approach

2.2.2. Approach from the model

With this approach, the impact of socio-economic activities and CC on water quality in the region will be comprehensively and quickly calculated and forecasted over space and time, ensuring reliability. The model used is Delf3D.

2.2.3. Interdisciplinary Approach

2.2.4. Inheriting existing documents

The thesis has inherited a rich and systematic source of documents, data, and valuable measurement, survey, and research findings.

2.3. Research methods

2.3.1. Document synthesis analysis method

Inheriting and utilizing data on natural, socio-economic, and environmental conditions in the research area, leveraging the available documents.

2.3.2. Statistical analysis methods

Statistical analysis method, the Mann-Kendall test and Sen's Slope are used to analyze the statistical characteristics of various factors such as water level and sea surface temperature, in order to assess the manifestations of CC.

2.3.3. GIS Method

The GIS method (with Global Mapper software) is used to process data, create grids, depth grids, and serve as input for the model.

2.3.4. Model method

2.3.4.1. Hydrodynamic model

This study employs the Delft3D model to investigate hydrodynamic processes and water quality in the CB-HL region. This is a three-dimensional (3D) integrated model created by the Delft Hydraulics Institute (Netherlands), encompassing fundamental modules such as hydrodynamics (Delft3D-Flow), waves (Delft3D-Wave), sediment transport (Delft3D-Sed), water quality (Delft3D-Waq), and ecology (Delft3D-Eco). This model effectively simulates hydrodynamic-wave conditions, sediment transport, and water quality in coastal river estuaries and has been extensively utilized in pertinent studies in Vietnam.

The coastal hydrodynamic model CB-HL employs an orthogonal curvilinear grid system. The model's calculation area encompasses the coastal river mouth regions, ranging from the northern waters of Ha Long Bay to the southern mouth of Tra Ly. The calculation domain spans roughly 143 km in the East-West orientation and 119 km in the North-South and Southeast orientation, partitioned into 697 x 308 calculation points, with grid cell sizes ranging from 17.7 to 670.3 m. The grid cells in the vertical dimension employ the σ-coordinate system, five water layers.

Wave model

This study's wave model is configured to operate concurrently (online coupling) with the hydrodynamic and the sediment transport models. At each hourly calculation (1 hour), the wave model will utilize the grid, wind field, and the outcomes of depth, water level, and flow computations from the hydrodynamic model.

2.3.4.2. Water quality model

The water quality model is established in three dimensions (3D) with five depth layers. The computational domain covers the entire sea area of the Gulf of Tonkin region. The water quality model also uses hydrodynamic modeling results.

The primary computed parameter groups consist of dissolved organic matter (BOD, COD), dissolved nutrients of nitrogen (NH_4^+, NO_3^-), phosphorus (PO_4^{3-}), and dissolved oxygen (DO)

2.3.4.3. Simulation scenarios

With the goal of assessing the impacts of human activities and CC, simulation scenario groups have been established, including:

Model validation scenario group: This scenario group will be established with the conditions of 2021, such as topography, meteorological, hydrological, oceanographic, and environmental conditions, in order to validate the model by comparing the model results with the measured data in 2021.

Present scenario group: conducted to simulate the assessment of hydrodynamic conditions, and water quality in the CB-HL area in 2019.

Scenario group of human impact: increases waste discharge into the CB-HL coastal area in 2030 and before the land reclamation activities in 2010

The scenarios simulating the impacts of climate change (sea level rise and rising temperature) in 2030 and 2050 are based on the CC scenarios of the Ministry of Natural Resources and Environment in 2020.

Group of scenarios integrating human and climate change impacts: would encompass the concurrent consequences of heightened pollutant sources, diminished bay area due to land reclamation, sea encroachment, SLR, and elevated sea temperatures (CC) in 2030 and 2050.

Each scenario will be simulated over the 4 seasons (Northeast monsoon, Southwest monsoon, and 2 transitional seasons), with duration interval of 30 seconds.

2.3.4.4. Model calibration and validation

Water elevation at Hon Dau and Bai Chay stations in Jannuary and October, 2021 was used to calibrate and validate the model. From the calculations, NSE coefficients indicated excellent matching between simulations and measurements with values of 0.91-0.95 for Hon Dau and 0.93 - 0.97 for Bai Chay.

Current velocity/direction was validated by comparing model results with data measured at Cua Luc, Ha Long, Tuan Chau, and Cam Pha stations in January and October, demonstrating a satisfactory correlation between simulations and measurements. The NSE coefficient varies 0.55- 0.65 and 0.58-0.71 for magnitude and current direction, respectively.

The simulation's findings are compared to observed organic matter (BOD, COD) and nutrients (NO_3^-, NH_4^+, PO_4^{3-}) at stations Cua Luc, Ha Long, Tuan Chau, and Cam Pha. They show a good matching of the simulations and observations, with the NSE ranging from 0.54 to 0.67 and 0.56-0.68, respectively.

2.3.5. Expert method

Through scientific conferences, thematic reports, and seminars, doctoral candidates will gather feedback from experts in related fields to enhance their thesis outcomes.

CHAPTER 3. RESULTS AND DISCUSSIONS

3.1. The manifestations of climate change in the Cat Ba-Ha Long area

3.1.1. The trend of rising sea levels

3.1.1.1. Changes in water level over time

At the Hon Dau station, the water level fluctuated over various periods: 183.66 cm, 191.68 cm and 197.27 cm during 1961-1980, 1981- 2000, and 2001-2020, respectively.

3.1.1.2. Trend of rising water levels

SLR at the Hon Dau and Bai Chay stations was assessed based on the Mann-Kendall (MK) method and Sen's Slope for both the full duration and a continuous 20-year interval. The findings indicate that SLR at the Hon Dau station is 3.38 mm/year (1961-2020) and 4.18 mm/year (1981-2020) at the Bai Chay station.

3.1.2. The increasing trend of sea surface temperature

3.1.2.1. Changes in water temperature

At the Hon Dau station from 1995 to 2020, the water temperature progressively grew from January to March, surged significantly from March to May, peaked in June-July at approximately 30.2°C, and thereafter declined until January. The mean sea temperature exceeds 28°C from May (28.5°C) to September (29.7°C). Conversely, the temperature remains nearly below 22°C from December (21.1°C) to March (21°C), with January recording the lowest temperature.

3.1.2.2. Temperature increase trend

The mean annual temperature at Hon Dau station has exhibited an upward trend of approximately 0.02°C per year. At the Bai Chay station, the surface water temperature increased at a rate of 0.052°C per year from 1995 to 2020.

3.2. Model Calibration and Verification

3.2.1. Hydrodynamic model

The hydrodynamic model has been calibrated and validated with measurements. After the final calibration, the NSE coefficient varies from 0.54-0.62 and 0.55-0.68 respectively with the magnitude and direction of the flow. The NSE coefficient for model verification is 0.55-0.65 for velocity and 0.58-0.71 for flow direction. The average difference between simulation and measurement (BIAS) is about -0.03 to 0.06 m/s (speed) and -10.2 to 20.3o (direction). The RMSE is between 23.2 and 35.5o for direction and from 0.03-0.05 m/s for velocity.

3.2.2. Water quality model

The simulation results were compared with organic matter (BOD5, COD) and nutrition ($NO3^-$, NH4+, PO43-) monitored at LT1-LT5 stations. After the calibrations, the validation results showed quite similar results between the simulation and observation results, with the NSE coefficients ranging from 0.54 to 0.67 and 0.56-0.68, respectively. RMSE values ranged from 0.15 to 0.29 mg/l and from 3.3 to 5.2 µg/l for organic and nutrient substances, respectively. The BIAS coefficient fluctuated between -0.001 and 0.004 mg/l for organic substances and from -1.79 to 0.91 µg/l for nutrients, indicating the fit that existed between simulations and observations.

3.3. The impact of socio-economic activities and climate change on environmental conditions

3.3.1. Flow

The impact of CC (mainly sea level rise and the increase in temperature) on the flow conditions in the study area were also simulated for the years 2030 and 2050. The results of the analysis and calculations show that the impacts of CC on the hydrodynamic conditions of the study area are modest and do not clearly manifest as trends. The impacts of human activities on hydrodynamic conditions in the CB-HL area are most evident from land reclamation, filling, and alteration of the seabed in the coastal waters.

3.3.2. Water temperature

The temperature in the CB-HL area fluctuates significantly by season. The impact of CC (elevated air temperature and SLR) indicates that the trajectory of water temperature alterations in 2030 and 2050 closely resembles existing scenarios. However, the baseline water temperature in the study area in the forecast scenarios increase significantly compared to the current scenario (2019), with values of approximately 0.5-1.0°C (2030) and 1.0-2.0°C (2050).

3.3.3. Salinity

Salinity in the CB-HL coastal region exhibits spatial and temporal fluctuations, influenced by tidal water levels and river flow. Projections for 2030 and 2050 indicate that salinity trends will closely resemble those observed in 2019. Low salinity remains predominantly concentrated in Cua Luc Bay, particularly from the river to the river mouth, with greater stability observed further offshore. Despite rising temperatures and SLR due to CC, their effects on salinity distribution in the area are minimal.

3.4. Impact of socio-economic activities and climate change on the water environment in the Cat Ba-Ha Long area

3.4.1. Impact of socio-economic activities on water quality

3.4.1.1. Individual impact due to increased sources of pollutants

The findings indicate that an increase of pollution sources in the CB-HL coastal area leads to significant variations in dissolved oxygen (DO) levels over time and across different locations. The distribution of DO closely resembles the present scenario (2019). The proliferation of pollution sources has markedly diminished DO levels in the water, particularly in coastal regions such as Cua Luc Bay, Ha Long Bay, the southwestern part of Cat Ba Island, and notably the northern region of Tuan Chau Island.

The analysis of average DO levels at various locations, including Cua Luc, Ha Long, Tuan Chau, Cam Pha, and Bai Chay, indicates a general trend: with increases in pollution loads by 2030, DO levels are expected to decline relative to the present scenario, displaying pronounced seasonal fluctuations. During the northeast monsoon, the DO concentration diminishes by 0.15-0.21 mg/l. The Bai Chay area exhibits the most significant decline in DO levels compared to other regions, recording a value of 0.21 mg/l, succeeded by the southern part of Tuan Chau Island at 0.18 mg/l, the Cua Luc and Cam Pha areas (0.17 mg/l), and the central area of Ha Long Bay at the lowest level of 0.15 mg/l. During the transitional wind season from northeast to southwest, the DO content is lower than in other seasons; however, the decline is more notable, especially in the southern region of Tuan Chau Island and Ha Long Bay, where it may exceed 0.4 mg/l.

During the southwest monsoon, the rise in nutritional and organic sources correlates with a decrease in DO by around 0.14-0.16 mg/l, exhibiting minimal variation between the regions. While, during the transitional season from southwest to northeast winds, the influx of pollution sources into the research region results in a modest drop in DO concentration compared to the present scenario. The mean DO value diminishes by 0.07-0.15 mg/l, representing the lowest level over the seasons.

3.4.1.2. Specific impacts due to land reclamation

Land reclamation activities in the CB-HL coastal region have modified the hydrodynamic characteristics of the coastal waters, significantly influencing the dispersion and transportation of pollutants in this area. During the transitional wind season from southwest to northeast, land reclamation might diminish the dissolved oxygen (DO) levels in Ha Long Bay, particularly in the northern region of Tuan Chau Island.

The data indicates that during the northeast monsoon season, the average DO concentration in the Cua Luc area had a minor decline of 0.04 mg/l, but other locations exhibited a trend of increasing DO levels following land reclamation. The DO levels rose significantly in the southern region of Tuan Chau Island (0.32 mg/l), followed by the coastal area of Bai Chay (0.2 mg/l) and Cam Pha (0.18 mg/l), with the lowest in Ha Long Bay (0.02 mg/l). During the transitional wind season from northeast to southwest, land reclamation diminishes DO levels in the coastal regions of Bai Chay and southern Tuan Chau, recording values of 0.17 and 0.25 mg/l, respectively. In contrast, in the remaining regions, land reclamation marginally elevates DO by 0.03-0.12 mg/l.

Following land reclamation, the average biochemical oxygen demand (BOD) typically rises over the seasons, observed in most regions, with values between 0.002 and 0.172 g/m^3. The peak increase in BOD value transpires during the northeast monsoon season, reaching 0.172 g/m^3 in the Cua Luc region. In the Cua Luc region, Ha Long and Cam Pha, during the transitional wind season from northeast to southwest, and in the Cua Luc, south of Tuan Chau Island during the southwest wind season, BOD diminished compared to the period preceding land reclamation activities, with values ranging from 0.047 - 0.068 g/m^3 and 0.009 - 0.063 g/m^3, respectively.

The average COD value post-land reclamation activities generally rises, particularly during the northeast monsoon and the transitional season from southwest to northeast, with values ranging from 0.002 to 0.076 g/m^3, except in the Cam Pha area, which exhibits a declining trend of 0.21 g/m^3. Conversely, during the transitional season from northeast to southwest winds and the southwest monsoon, COD tends to decrease, exhibiting values between 0.02-0.1 g/m^3, with the exception of the Ha Long area, where it experiences a minor rise (0.001 g/m^3).

The average NO_3^- concentration fluctuates across various regions and seasons. During the northeast monsoon season, a rising trend of $NO_3^-$is noted in all five regions affected by land reclamation, with a value of 0.004-0.007 g/m^3. Conversely, a declining tendency is evident in the majority of regions during the subsequent seasons, with levels below 0.01g/m^3.

Following reclamation activities, the average NH_4^+ concentration tends to increase during the northeast monsoon and the transitional period from southwest to northeast, with levels reaching up to 0.0064 g/m^3. The rising trend of NH_4^+ during the transitional season from southwest to northeast is more significant than in the northeast monsoon. The declining tendency across all five areas was observed during the transitional from northeast to southwest winds, manifesting in the southern regions of Tuan Chau Island and Cam Pha in the southwest monsoon.

The average PO_4^{3-} concentration exhibits an upward tendency at most locations throughout the northeast monsoon, southwest monsoon, and the transitional period from southwest to northeast monsoon (excluding the Cam Pha area), with concentrations between 0.001-0.007g/m^3 after reclamation activities. The opposite trend occurs during the transitional season from northeast to southwest, characterized by a reduction of 0.003-0.007 g/m^3, with the exception of the southern part of Tuan Chau Island, which exhibits a marginal increase of 0.001 g/m^3.

The aforementioned analyses indicate that the influence of land reclamation activities on the water environment in the studied area is notably intricate. The magnitude of impact, both beneficial and detrimental, fluctuates with time and seasons, as well as across various sites within the CB-HL coastal region.

3.4.2. Impact of climate change on water quality

The result indicates that CC causes a decline in DO levels in water. During the northeast monsoon, the average DO concentration diminishes by 0.06 mg/l in the 2030 scenario and by 0.1 mg/l in the 2050 scenario. During the transitional season from northeast to southwest winds, the DO concentration, according to CC projections for 2030 and 2050, diminishes by 0.04 and 0.06 mg/l, respectively. The declining trend is particularly evident during the southwest monsoon, with the average DO content in the monitored regions projected to fall by 0.27 mg/l and 0.29 mg/l according to CC scenarios for 2030 and 2050, respectively. During the transitional season from southwest to northeast winds, the DO concentration diminishes by 0.03 mg/l and 0.04 mg/l for the CC scenarios of 2030 and 2050, respectively

The increase of water level and temperature may diminish BOD in the coastal area, with values of 0.005 - 0.011 g/m^3 and 0.019 - 0.046 g/m^3 during the northeast monsoon and the transition from northeast to southwest monsoon, respectively. In the 2030 simulation scenario, BOD values exhibit a modest increase during the southwest monsoon and the transition from southwest to northeast, recording values of 0.009 g/m^3 and 0.006 g/m^3, respectively. The modeling scenario for 2050 revealed an opposing trend: a reduction of 0.028 g/m^3 during the southwest monsoon and 0.02 g/m^3 in the transitional season from southwest to northeast. The average COD values generally decline in most regions across the scenarios, particularly exhibiting a more significant reduction under the impact of CC in 2050. During the northeast monsoon, the transitional seasons from northeast to southwest and from southwest to northeast, the COD diminishes with value ranges of 0.006-0.012 g/m^3, 0.024-0.053 g/m^3, and 0.009-0.019 g/m^3, respectively. During the southwest monsoon, COD is projected to increase marginally in the 2030 scenario (0.01 g/m^3) and decrease in the 2050 scenario (0.014 g/m^3).

Due to climate change, the nutrient contents in the water exhibit little variation relative to the present scenario. The average nutrient concentration in the five locations may increase/decrease by a maximum of approximately 0.001 g/m^3 for NO_3^- and PO_4^{3-}. A decreasing trend was seen for NH_4^+ in most regions, with a value potentially reaching 0.005 g/m^3.

The suspended sediment concentration shows an increasing trend in the forecast scenario for 2050 under the influence of CC, with values of 0.6 - 1.22 g/m^3 (Northeast monsoon), 0.82 - 2.5 g/m^3 (transition season from Northeast to Southwest monsoon), 1.36 - 5.27 g/m3 (Southwest monsoon), and 0.89 - 3.35 g/m^3 (transition season from Southwest to Northeast monsoon).

The rise in temperature due to CC has been identified as a significant element influencing water quality. Sea water temperature is a pivotal determinant in the physical-chemical balance processes, including nitrification and the mineralization of organic compounds. Consequently, variations in water temperature will modify the transport and dispersion of organic matter and dissolved nutrients in coastal river estuaries.

The research findings in the CB-HL coastal area demonstrate that CC (elevated temperatures, SLR) leads to a reduction in water oxygen levels, averaging roughly 0.02-0.28 mg/l by 2030 and 0.03-0.31 mg/l by 2050. This research finding aligns with studies indicating that elevated temperatures lead to a reduction in dissolved and saturated oxygen levels in water.

Furthermore, climatic change diminishes NH_4^+ levels (0.005 g/m^3) and may alter NO_3^- and PO_4^{3-} concentrations by approximately 0.001 g/m^3 in the CB-HL region. A recent study indicates that elevated water temperatures can diminish nitrogen and phosphorus nutrient levels from the river to the coastal zone, attributed to enhanced consumption and photosynthesis by algae, as phytoplankton flourish with rising temperatures.

3.4.3. Impact of socio-economic activities and climate change on water quality

Alongside examining the individual effects of socio-economic activities and CC, the scenario group also simulated the combined impacts of human activities and CC on the water environment for the years 2030 and 2050. The analysis results show that the spatial variation trends of the water environment in the area do not differ much between the scenarios. The spatial distribution of pollutants reveals a consistent pattern: elevated concentrations are predominantly located in the coastal regions of the river mouth, extending from the Cua Luc Bay to the southern section of Cat Hai Island, particularly in areas such as Cua Luc, Chanh River, and the northern part of Tuan Chau Island. The scenario groups that combine human impact and CC and the scenario caused solely by humans lead to a significant increase in organic and nutrient substances while simultaneously reducing DO compared to the current scenario groups and the scenario that only considers CC. This is clearly evident at the coastal river mouth region; however, the disparities between the scenarios become nearly imperceptible as one moves inland. The temporal variation pattern of the contaminated water masses predominantly aligns with tidal oscillations, exhibiting minimal differences across the scenarios.

The analytical results demonstrate that a rise in pollution sources correlates with a drop in DO content relative to current conditions (2019). During the northeast monsoon season, influenced by CC, the DO content diminishes, recording values of 0.05-0.07 mg/l in 2030 and 0.08-0.13 mg/l in 2050. The trend of diminishing DO is significantly exacerbated by anthropogenic factors, particularly the combination of CC and human activities: 0.15-0.21 mg/l (2030h); 0.2-0.26 mg/l (2030h-cc); and 0.23-0.3 mg/l (2050h-cc).

During the transitional wind season from northeast to southwest, DO levels dramatically decline in scenarios affected by anthropogenic activity, particularly in the context of combined human impact and CC, with values of 0.09-0.44 mg/l (2030h), 0.15-0.48 mg/l (2030h-cc) and 0.17-0.4 mg/l (2050h-cc), respectively. In the absence of other factors, CC alone results in a reduction of DO concentration in water by approximately 0.03-0.06 mg/l (2030cc) and 0.04-0.09 mg/l (2050cc).

During the southwest monsoon, the trend of declining DO persists across scenarios; however, due to CC, the reduction in DO content is more pronounced than in the human impact scenario. CC results in a drop of DO by 0.25-0.28 mg/l (2030cc) and 0.27-0.31 mg/l (2050cc), whereas human impact causes a reduction of 0.14-0.16 mg/l (2030h), 0.11-0.14 mg/l (2030h-cc), and 0.13-0.17 mg/l (2050h-cc).

During the transitional wind season from southwest to northeast, the synergistic effects of human activities and CC diminish the DO level in water more significantly than each factor alone. The effect of CC decreases the DO value by approximately 0.02-0.03 mg/l (2030cc) and 0.03-0.05 mg/l (2050cc), whereas human activity has diminished the DO by 0.07-0.15 mg/l (2030h), 0.09-0.18 mg/l (2030h-cc), and 0.1-0.2 mg/l (2050h-cc).

The simulated scenarios for the combined effects of human activity and CC in 2030 and 2050 indicate an increase in organic compounds (BOD and COD) in the research area. BOD and COD exhibit considerable similarity, with values increasing from 0.074 to 0.3 g/m^3 and 0.078 to 0.32 g/m^3, respectively, and are often lower than those in scenarios solely influenced by human activity. A contrasting pattern emerges when solely the effects of CC are evaluated, resulting in reductions of 0.005-0.046g/m^3 (BOD) and 0.006-0.053g/m^3 (COD).

Under the combined influence of humans and CC, the nutrient content in the areas has increased in all seasons, with an increase of 0.006-0.025g/m^3 (NO_3^-); 0.006-0.019g/m^3 (NH_4^+) and 0.002-0.011g/m^3 (PO_4^{3-}).

The concentration of suspended sediments, influenced by human socio-economic activities, exhibits an upward trend relative to the current scenario, with values between 0.0005-1.627g/m^3. Conversely, in the scenario solely affected by CC, there is a downward trend, with values below 0.66g/m^3 during the Northeast monsoon and the two transitional seasons. During the Southwest monsoon season, an upward trend is observed in the majority of scenario groups, with values between 0.03 and 2.41 g/m^3, whereas a downward trend is noted just in the CC-influenced scenario for 2050 (0.077-0.26 g/m^3).

Both anthropogenic activities and CC influence water quality during the northeast monsoon and the two transitional seasons; however, the effect of CC (DO reduction of 0.02-0.13 mg/l) is less significant than that of human activities (DO reduction of 0.07-0.44 mg/l), while their combined impact results in a DO reduction of 0.09-0.48 mg/l. During the southwest monsoon, the trend reverses: the impact of CC significantly reduces water quality (DO declines by approximately 0.25-0.31 mg/l), surpassing that of human activities (0.14-0.16 mg/l), and the combined effect of human activities and CC (0.13-0.17 mg/l). Conversely, due to human activity and CC, nutrient concentrations in the area have risen, with average values of 0.002-0.033 g/m^3 (NO_3^-), 0.0003-0.034 g/m^3 (NH_4^+), and 0.0005-0.014 g/m^3 (PO_4^{3-}).

The CB-HL coastal area has experienced an increase in organic matter concentration (0.32 g/m^3) and nutrients (0.025 g/m^3) due to human activities, such as rising pollutants and land reclamation, Concurrently, the concentration of dissolved oxygen has diminished to 0.33 mg/l. Jeppesen et al (2005) posited that forecasting the effects of augmented nutrient input from terrestrial sources and CC are very intricate processes, characterized by interacting influences among nutrient sources, light conditions, temperature, and hydrodynamic factors. The augmentation of fertilizer sources along the shore, along with elevated sea temperatures, will create very favorable conditions for the proliferation of algae, particularly blue-green algae. The augmentation of nitrogen nutrients from anthropogenic activities, along with the effects of CC, can substantially elevate nitrate concentrations in certain regions. The findings closely resemble those of Whitehead et al. (2006) in the Thames estuary, predicting that nitrate concentrations may climb from 4 to 18 mg/l due to the synergistic effects of fertilizer influx and temperature elevation resulting from CC. An additional announcement indicated that with the increase in water temperature by about 0.8-1.1 degrees Celsius in the Chesapeake Bay (USA), coupled with the augmented nutrient influx due to socio-economic development, has led to a substantial increase in phytoplankton biomass and a heightened frequency of red tide events in this region (Miler and Harding, 2007).

The rise in temperature and alterations in precipitation, with anthropogenic influences like population expansion, livestock, and modifications in land use, will persist in influencing the flow and water quality of rivers and coastal areas (Jin et al., 2015).

3.5. Proposed management solutions

3.5.1. Group of propaganda solutions

The study indicates that both climate change and human activities impact the water environment in the CB-HL area, with coastal pollution sources being the primary cause of water quality degradation. Although the current effects of climate change are relatively minor, alarming signs such as sea level rise and increasing sea surface temperatures are evident. Therefore, it is crucial to strengthen communication and community education on marine resource protection. Visual tools and modeling results from this study should be used to raise awareness among residents, students, and tourists. Community participation is a key factor in reducing emissions, protecting the environment, and ensuring the sustainable development of tourism and services in the region.

3.5.2. Control of pollution sources introduced into the CB-HL area

Socio-economic development activities in the CB-HL area are mainly population growth, tourism, agricultural activities, animal husbandry, and industry, which have given rise to pollutants into the water environment in the area:

- Human socio-economic activities are the main factors causing local pollution at some times, causing loss of aesthetics and deterioration of water quality in some coastal areas such as Cua Luc Bay, Ha Long, Tuan Chau Island, the west and northwest of Cat Ba Island, etc. Therefore, it is necessary to control pollution sources introduced into the CB-HL area: Treat wastewater sources before discharging into the environment; supervise and measure water quality (WQ) at waste discharge locations.

- The monitoring of water quality in the CB-HL area is carried out quarterly by the Ha Long Bay Management Board. However, the monitoring results are only carried out at certain locations and times, which is difficult to evaluate, as well as give an overall picture of the water environment in the CB-HL area. The Delft3D model used in the thesis has been established to simulate WQ well under different scenarios. This is one of the useful tools to assess the spread and spread of pollutants in the CB-HL area.

Increasing resource support for water environment management: Increasing investment in building a network of water environment monitoring points in CB-HL waters; It is necessary to strengthen training and fostering knowledge on state management of water and environmental resources; Strengthen inspection and examination of the implementation of commitments on environmental protection as well as commitments in the discharge permit into water sources.

3.5.3. Group of solutions for enhancing climate change research and adaptation measures

Research on CC manifestations in this study only extends up to 2021, while CC continues to evolve in increasingly complex and unpredictable ways. As a slow-occurring phenomenon that spans decades, many short-term changes may go unnoticed. Long-term observational data indicate that the CB-HL region has been significantly affected by CC, with sea level rising at a rate of 3.38-4.18 mm/year and temperature increasing by 0.02-0.052°C/year. Notably, in recent years, these rates have accelerated to 4.72-7.16 mm/year and 0.093-0.103°C/year, respectively. Therefore, it is necessary to enhance research efforts to comprehensively assess the impacts of CC on water quality and marine ecosystems in the CB-HL area.

Strengthening research on adaptation strategies is also essential, as CC is a global phenomenon with long-term, cumulative effects. Although current impacts on water quality in the CB-HL region remain moderate, it is vital to understand the underlying mechanisms, trends, and influences of CC (including temperature rise, sea level rise, and extreme weather events) to improve forecasting accuracy and propose effective adaptation solutions.

3.5.4. Group of solutions for integrating climate change into socio-economic development planning

The impacts of CC and socio-economic development on the water environment in the CB-HL region are complex, requiring the integration of CC considerations into socio-economic development planning. This approach ensures sustainable development and effective adaptation to risks such as sea level rise, rising temperatures, and extreme weather events. Specifically, CC adaptation should be integrated into socio-economic development planning; clean and environmentally friendly production should be encouraged to minimize pollutant discharge into the CB-HL area; aquaculture activities in the region should be restricted; and climate-related risks must be considered in the planning of coastal residential areas and industrial zones.

3.5.5. Group of solutions to protect ecosystems and sensitive areas

The water quality model results indicate that pollution is primarily concentrated in nearshore areas close to discharge sources. However, under specific hydrodynamic conditions (such as the ebb phase of spring tides), sensitive offshore zones in Ha Long Bay and Cat Ba can also be affected. Therefore, it is necessary to identify and categorize vulnerable areas, conduct regular water quality monitoring, and utilize model outputs to determine specific pollution sources in order to propose effective control measures.

3.5.6. Sustainable development planning solutions

Marine spatial planning should be based on research findings related to hydrodynamics and the marine environment, particularly those derived from flow modeling, water exchange capacity, and pollutant dispersion simulations. These results provide a scientific basis for rational zoning of tourism, conservation areas, no-exploitation zones, and anchorage sites, thereby minimizing spatial use conflicts and enhancing the environmental resilience of the CB-HL area.

Model results indicate that pollution is currently concentrated near coastal discharge sources; however, in the long term, it is essential to assess the environmental carrying capacity (i.e., the ability to assimilate pollutants) of the entire CB-HL area. This assessment will support policymakers in balancing socio-economic development with sustainable environmental protection.

3.5.7. Application of science and technology in monitoring and early warning

Modeling results indicate that the degradation of water quality in the CB-HL area primarily originates from coastal point-source discharges. The emergence of additional pollution sources could expand the affected areas over time. The simulation outcomes also help identify vulnerable zones, which can inform the development of an automated environmental monitoring system at high-risk locations. This approach is cost-effective while ensuring timely detection and response to pollution incidents.

Environmental management staff of the Ha Long Bay Management Board should be equipped with advanced technologies and techniques to support water quality management. These include the use of remote sensing imagery for environmental monitoring, digital modeling tools for water quality assessment and forecasting, and pollutant dispersion simulation in case of environmental incidents.

CONCLUSION AND RECOMMENDATION

Conclusion

In order to evaluate and forecast the impacts of human socio-economic activities and CC (temperature increase and SLR) on WQ in CB-HL waters, a system of WQ-Wave model based on the Delft3D model has been established. In order to serve the establishment and verification of the results of the model, relevant data sets in the region have been collected and processed. The comparative results between the calculation by the model and the observation show that there is a relative agreement and this model can be used as an effective tool to study and forecast the impacts of human socio-economic activities and CC on the WQ of the CB-HL waters. Different groups of simulation scenarios have been established: model verification scenario (2021), status quo scenario (2019); CC impact scenarios (2030 and 2050); scenarios of socio-economic impacts (increasing pollution sources by 2030 and scenarios when there are no sea encroachment activities in 2010); scenarios combining human impacts and CC (2030 and 2050). The results of the assessment of CC manifestations as well as human and CC impacts on the CB-HL sea area are as follows:

The manifestations of CC in the CB-HL area have been analyzed and evaluated by the Mann-Kendall and Sen's Slop methods through a number of factors of water temperature and water level in stations such as Bai Chay and Hon Dau. The results show that the water level at both Bai Chay and Hon Dao stations has decreased with values of 4.18mm/year (1981-2020) and 3.38mm/year (1961-2020), respectively. SLR has tended to increase rapidly in the recent period (2001-2020), reaching 4.72mm/year (Bai Chay station) and 7.16mm/year (Hon Dau station). The temperature at Hon Dau station increased by 0.02^{o}C/year and tended to increase faster than at Bai Chay station with 0.052^{o}C/year in the period 1995-2020. The growth rate of water heat reached 0.093^{o}C at Hon Dau station and 0.103^{o}C at Bai Chay station in the period 2008-2020.

The effects of humans and climate change in the northeast monsoon season and the 2 transitional seasons both reduce CLN (DO), but the effects of climate change with only 0.02-0.13 mg/l (0.3-2.0%) are smaller than those of humans at 0.07-0.44 mg/l (1.0-7.2%) and the scenario with a combination of human activities and climate change is 0.09-0.48 mg/l (1.3-8.0%). Meanwhile, in the southwest monsoon season, this trend has the opposite development: the impact of climate change sharply degrades water quality with a value of 0.25-0.31 mg/l (3.9-5.0%) greater than the impact caused by human activities of 0.14-0.16 mg/l (2.2-2.5%) and the combined impact of human activities and climate change is 0.13-0.17 mg/l (1.8-2.8%). The combined effects of human activity and climate change increased the organic indicators, with the increased values ranging from 0.074-0.3 g/m^3 (2.8-19.1%) for BOD and 0.078-0.32 g/m^3 (2.8-19.0%) for COD. Nutrients in the regions also increased with values of 0.006-0.025 g/m^3 (9.2-106.9%), 0.006-0.019 g/m^3 (1.2-86.2%) and 0.002-0.011 g/m3 (3.0-80.6%) respectively NO_3^-, NH_4^+ and PO_4^{3-}.

On the basis of assessing the separate impacts of humans, CC and the combined impacts of humans and CC on the WQ of the CB-HL waters, a number of groups of solutions have been proposed, including: 1) Propaganda solutions; 2) Control the source of pollution brought into the CB-HL area; 3) Group of solutions to mitigate the impact of climate change; 4) Group of solutions to reduce the impact of socio-economic activities due to climate change; 5) Group of solutions to protect ecosystems and sensitive areas; 6) Sustainable development planning solutions; 7) Early monitoring and warning.

Recommendations

Within the framework of the thesis, the PhD student only assesses the impact of human beings on increasing pollutants from socio-economic development activities, but has not assessed in case of incidents occurring such as from industrial parks to WQ in the CB-HL area. Due to the impact of incidents from industrial zones that can have serious consequences on ecosystem as well as WQ, typically the Formusa incident in Central Vietnam in 2016 caused heavy damage to the socio-economy and environment of 4 provinces of Ha Tinh, Quang Binh, Quang Tri and Thua Thien Hue. This study focused on evaluating the effects on the water environment based on groups of organic pollutants, nutrients and oxygen without evaluating other substances as well as ecosystem in the CB-HL area. In addition, the impact of CC in this study only takes into account the increase in temperature and SLR, but does not take into account extreme weather phenomena such as rain, floods, storms, etc. All these limitations will be overcome by the PhD student in future studies.

The Delft3D model is one of the effective tools that can assess the spread and dispersion of pollutants, giving an overall picture of the water environment at any time or area, especially when an incident occurs. This model has been applied to CB-HL waters where there is a complex terrain with many small islands, so it can be applied to other waters in Vietnam.

NEW FINDINGS OF THE THESIS

- Manifestations of climate change (sea level rise and sea temperature increase) in CB-HL waters based on analysis results from the latest monitoring data to 2020 (the time of implementation of the thesis).

- Separate/combined impacts of socio-economic activities (increasing pollution sources and sea encroachment) and climate change (sea level rise and temperature increase) on the water quality of CB - HL waters based on the calculation/forecast results of the numerical model.

LIST OF THE PUBLICATIONS RELATED TO THE DISSERTATION

1. **Hai, N.M.;** Vinh,V.D.; Ouillon, S.; Lan, T.D.; Duong, N.T. 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* 2025, 17, 319. https://doi.org/10.3390/w17030319

2. **Minh Hai Nguyen**, Duy Vinh Vu, Duc Thinh Nguyen, Thanh Duong Nguyen (2024). Numerical investigations on seasonal variation of waves in the Cat Ba – Ha Long coastal area (Vietnam) in 2021. *Regional Studies in Marine Science* 79 (2024) 103828.

3. Vu Duy Vinh, **Nguyen Minh Hai**, Saheed Puthan Purayil, Genevieve Lacroix, Nguyen Thanh Duong (2024). Seasonal variation of coastal currents and residual currents in the Cat Ba –Ha Long coastal area (VIET NAM): Results of coherens model. *Regional Studies in Marine Science* 80 (2024) 103874. https://doi.org/10.1016/j.rsma.2024.103874

4. **Nguyen, Hai M.,** Sylvain Ouillon, and Vinh D. Vu (2022). Sea Level Variation and Trend Analysis by Comparing Mann–Kendall Test and Innovative Trend Analysis in Front of the Red River Delta, Vietnam (1961–2020), *Water*, 14(11):1709. https://doi.org/10.3390/w14111709

5**. Nguyen Minh, H.,** Ouillon, S., & Vu Duy, V. (2022). Sea-level rise in Hai Phong coastal area (Vietnam) and its response to enso - evidence from tide gauge measurement of 1960-2020. *Vietnam Journal of Earth Sciences*, 44(1), 109–126. https://doi.org/10.15625/2615-9783/16961.

6. Vu Duy, V., Ouillon, S., & **Nguyen Minh, H**. (2022). Sea surface temperature trend analysis by Mann-Kendall test and sen's slope estimator: a study of the Hai Phong coastal area (Vietnam) for the period 1995-2020. *Vietnam Journal of Earth Sciences*, 44(1), 72–91.

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8. **Nguyen, M. H**., Ouillon, S., & Vu, D. V., 2021. Seasonal variation of suspended sediment and its relationship with turbidity in Cam - Nam Trieu estuary, Hai Phong (Vietnam). *Vietnam Journal of Marine Science and Technology*, 21(3). https://doi.org/10.15625/1859-3097/16076.

9. Vinh, V. D., Ouillon, S., & **Nguyen, M. H.,** 2021. Suspended sediment floc size in the Cam - Nam Trieu estuary (Hai Phong, Vietnam), in wet season. Vietnam Journal of Marine Science and Technology, 21(3). https://doi.org/10.15625/1859-3097/16074